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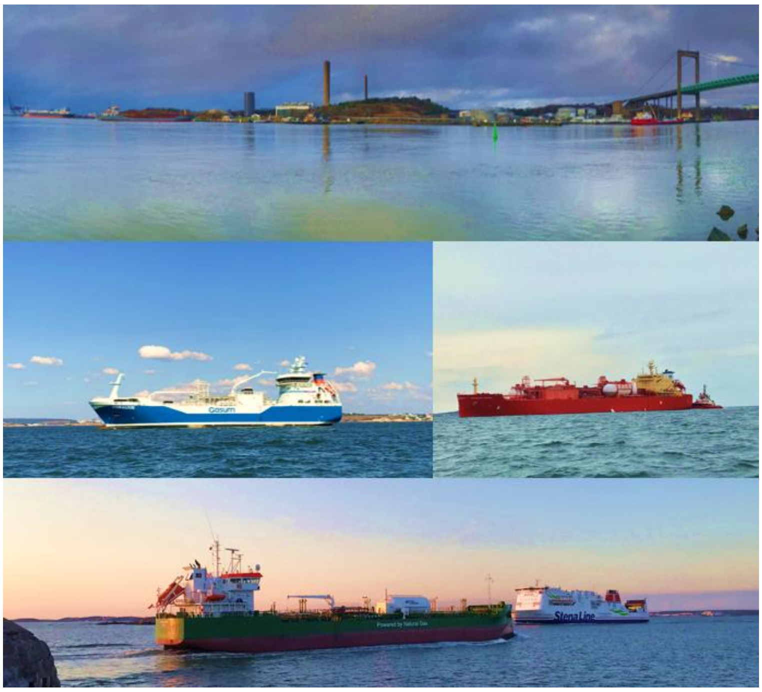

CAN LNG BE REPLACED WITH LIQUID BIO-METHANE (LBM) IN SHIPPING?

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THE SWEDISH KNOWLEDGE CENTRE
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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. P50435-1. 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 (see https://f3centre.se/en/about-f3/).

Shipping needs to phase out the usage of fossil fuels and until a couple of years ago, LNG (Liquefied natural gas) was seen as a part of that solution. This is because LNG contain less carbon per energy amount and hence also has the potential to lower the carbon dioxide emissions to some extent. Compared to traditional bunker fuels in shipping, such as MGO (Marine gas oil) and HFO (Heavy fuel oil), LNG also has the potential to substantially reduce for example particulate matter and sulphur oxides. But today, the reality of what is needed is more obvious to a larger part of the industry, as well as policy makers and the public. Switching to LNG is not enough unless it is combined with carbon removal in the form of CSS (Carbon Capture and Storage) or similar. Two decades have passed since LNG was introduced as a bunker fuel and made available in major ports, and LNG ships are predicted to make up for 10-40 % of all vessels in the future. Solutions are needed to solve the equation on how the decarbonisation of that part of the fleet shall be met.

This study investigates the possibility to replace LNG with renewable and sustainable produced methane in liquified form. The project started with the idea that marine transport could make use of the biogas that the bus fleet would no longer need after transitioning to electric propulsion. The biogas could potentially be liquified and sent to ships instead. From a ship-owner's perspective, the cost for switching to renewables is too high today. However, at the start of this study, an opening in policy shift that might provide support measures in that direction was discerned.

The policy progress within EU and the Fit for 55 package under the European Green Deal is a moving target that is constantly discussed and debated. Several additions and changes have happened during the approximately two years since this study was initiated. As an example, ship operations within EU waters is likely to be implemented in the EU emission trading scheme ETS from 2023. On a national level, the Swedish government recently decided on a production support incentive for biogas production of 500 MSEK in 2022, and 700 MSEK per year for 2023 and 2024. Details remain, but the decision itself made the lowest production scenarios in this study quite unlikely.

All in all, we are very thankful towards The Swedish Energy Agency and f3 that we have been financed to work with this study and hopefully contribute towards the realisation of the potential of producing up to approximately 30 TWh of LBM (Liquefied Bio Methane – se definition in this report) and CBG (Compressed biogas) annually in Sweden. This amount of renewable bio-methane and electromethane can solve a significant part of the decarbonisation of ship operations related to the vessels that bunker and will bunker methane in Swedish ports.

The project group has consisted of researchers from IVL and Chalmers, who are supplemented with a group of organisations and interested industry that have supported the project with information, experience, discussions related to analysis and results as well as good ideas for solutions and available resources, studies etc.

The organisations and persons that have supported the project are:

- Energigas Sverige – Fredrik Svensson, Johan Laurell
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Results related to this study will also be presented and published in a separate paper during 2022.

SUMMARY

As per today (2021), in total some 500 TWh bunker fuel is consumed within the shipping sector annually within EU waters and approximately 25 TWh of this (5%) is LNG (Liquefied natural gas). The fleet of LNG fuelled vessels has grown steadily since the first vessels were introduced around year 2000. Predictions and scenarios indicate that in a couple of years, it is likely that around 15 % of all bunker fuels consumed in shipping will be LNG.

Through detailed analyses of present and planned production capacity combined with scenarios built for future potential bio- and electro-methane production, a possibility to replace large amounts of LNG in shipping can be seen from a Swedish perspective.

In total, the analysis shows a maximum scenario for LBM production (Liquefied Bio Methane) in Sweden year 2045 of nearly 30 TWh annually. This potential includes electro-methane production based on carbon dioxide that is naturally formed during the biogas digestion production process. All production, of methane being assessed as potential, is assessed to be based on sustainable substrates and sustainably produced.

This report shows that it could be possible to replace fossil LNG as a fuel in shipping with renewable LBM at a large scale from a Swedish perspective. The total bunkering of ships in Sweden are around 25 TWh per year, varies over time, and is dependant not only on which ships that calls Swedish ports but also with the market competition with bunker suppliers in other countries. Should 15% of that fuel be LNG, it would be some 4 TWh LNG that could be interesting to switch towards renewable LBM.

The potential shift in shipping in Sweden from LNG to LBM at a level of 4-6 TWh is assessed to be a realistic potential, but the shift will not happen unless the society gives the industry incentives that supports that shift and clearly shows the involved stakeholders that there is a long-term strategy to enhance renewable methane production and consumption. It is especially important that policy instrument in the shipping sector is introduced that connects greenhouse gas emissions with a cost that can be avoided if fuels with low or zero emissions being used.

Today, only a small proportion of bio-methane is liquefied to LBM in Sweden, while most of the planned production facilities for biogas will be for LBM, thanks to subsidies in the form of investment support and the decreased demand of CBG that benefits LBM.

This report has chosen to use the expression Liquid Bio-Methane (LBM) due to the fact that the expression often used Liquid Bio Gas (LBG) does not cover the important part of the methane produced as an electrofuel based on carbon dioxide from the digestion process and also not really includes the methanation of syngas from gasification plants.

A Swedish production support in combination with the introduction of shipping within the EU emission trading scheme (ETS) seems too possibly even out the cost difference between LNG and LBG as a marine fuel or at least give a significantly smaller barrier to overcome.

To establish the environmental rationale of this product, life cycle assessments of the production of LBM and the use in the shipping sector were performed. No previous scientific studies have been

identified which look into the performance of using electrofuel pathways of LBM in the shipping sector. The results are presented in the report together with an analysis of potential future issues to observe.

SAMMANFATTNING

Idag (2021) förbrukas totalt cirka 500 TWh bunkerbränsle inom sjöfartssektorn årligen inom EU och cirka 25 TWh av detta (5 %) uppskattas vara LNG (Liquefied natural gas). Flottan av LNG-drivna fartyg har växt stadigt sedan de första fartygen introducerades runt år 2000. Förutsägelser tyder på att det inom ett par år är troligt att cirka 15 % av allt bunkerbränsle som förbrukas inom sjöfarten kommer att kunna vara LNG.

Genom detaljerade analyser av nuvarande och planerad produktionskapacitet kombinerat med scenarier byggda för framtida potentiell bio- och elektrometanproduktion ser vi en reell möjlighet att med dessa förnybara bränslen fasa ut stora mängder LNG inom sjöfarten. Detta sett ur ett svenskt perspektiv.

Totalt visar analysen ett maximalt scenario för LBM-produktion (Liquefied Bio Methane) i Sverige år 2045 på närmare 30 TWh årligen. Denna potential inkluderar elektrometanproduktion baserad på koldioxid som bildas naturligt under biogasrötningsprocessen. All produktion, av metan som bedöms som potentiell, bedöms vara baserad på hållbara substrat och vara hållbart producerad.

Denna rapport visar alltså att det skulle kunna vara möjligt att ersätta fossil LNG som bränsle inom sjöfarten med förnybar LBM i stor skala ur ett svenskt perspektiv. Den totala bunkringen av fartyg i Sverige ligger på cirka 25 TWh per år, varierar över tiden, och beror inte bara på vilka fartyg som anlöper svenska hamnar utan även av konkurrensen på bunkermarknaden med hamnar i andra länder. Skulle det vara så att 15 % av det bränslet är LNG, det skulle svara mot cirka 4 TWh LNG som kan vara intressant att byta mot förnybar LBM.

Det potentiella skiftet inom sjöfarten i Sverige från LNG till LBM på en nivå av 4–6 TWh bedöms vara en realistisk potential, men skiftet kommer inte att ske om inte samhället ger branschen incitament som stödjer det skiftet och tydligt visar de inblandade intressenterna att det finns en långsiktig strategi för att öka produktionen och konsumtionen av förnybar metan. Det är särskilt viktigt att ett styrmedel inom sjöfarten införs som kopplar samman utsläpp av växthusgaser med en kostnad som kan undvikas om bränslen med låga eller nollutsläpp av klimatgaser används.

Idag är det bara en liten del av biometan som förvätskas till LBM i Sverige, medan merparten av de planerade produktionsanläggningarna för biogas kommer att vara för LBM. Detta tack vare subventioner i form av investeringsstöd och den minskade efterfrågan på CBG som gynnar LBM.

Denna rapport har valt att använda uttrycket Liquid Bio-Methane (LBM) på grund av att det ofta använda uttrycket Liquid Bio Gas (LBG) inte täcker den viktiga delen av metan som produceras som ett elektrobränsle baserat på koldioxid från rötningen process och inkluderar egentligen inte heller metanisering av syngas från förgasningsanläggningar.

Ett svenskt produktionsstöd i kombination med införlivandet av sjöfart inom EU:s utsläppshandelssystem (ETS) ser ut att kunna jämna ut kostnadsskillnaden mellan LNG och LBG som marint bränsle eller åtminstone bli en mindre barriär att övervinna.

För att fastställa miljönyttan för denna produktionspotential gjordes livscykelbedömningar av produktionen av LBM och användningen inom sjöfartssektorn. Inga tidigare vetenskapliga studier har

identifierats som undersöker prestandan för att använda elektrobränslevägar för LBM i sjöfartssektorn. Resultaten presenteras i rapporten tillsammans med en analys av potentiella framtida frågor att observera.

CONTENTS

GLOSSARY / DEFINITIONS

Biofuel	Fuel from biogenic resources
Biogas	A mixture of methane (CH_4), carbon dioxide (CO_2) and small quantities of other gases produced by anaerobic digestion of organic matter in an oxygen free environment.
Bio-Methane	A near-pure source of renewable methane produced either by “upgrading” biogas (a process that removes any CO_2 and other contaminants present in the biogas) or through thermo and electrochemical pathways with subsequent methanation.
CAPEX	Capital expenditure
CBG	Compressed biogas
CHP	Combined heat and power (CHP) plants use the waste heat from electricity production for heating purposes
CBM	Compressed Bio Methane (synonym to CBG but including thermo and electrochemical pathways)
CO	Carbon monoxide
CO_2	Carbon dioxide
$CO_{2\text{-eq}}$	Carbon dioxide equivalent, greenhouse gases other than CO_2 are recalculated and expressed as carbon dioxide equivalents based on their warming potential in a defined time perspective
CCS	Carbon Capture and Storage
Drop-in fuel	A high-end biofuel (e.g. HVO) that is exchangeable in parts or in full with refined petroleum-based diesel fuel
DWT	Deadweight tonnage
e-CBM	Compressed Bio-Methane produced through electrochemical pathways
e-LBM	Liquid Bio-Methane produced through electrochemical pathways
External costs	External costs are costs carried by the society for e.g. environmental deterioration. E.g. Health care costs for increased cases of asthma due to air pollution
GHG	Greenhouse gases
HFO	Heavy fuel oil, a conventional fuel in shipping that mainly consists of residual oil from refineries
HVO	Hydrotreated vegetable oil, often used as a drop-in fuel in fuel for diesel engines
IEA	International Energy Agency
ILUC	Indirect Land Use Change
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standardisation Organization
LBG	Liquefied biogas
LBM	Liquefied Bio Methane (synonym to LBG but including thermo and electrochemical pathways)
LNG	Liquefied natural gas

LSFO	Low sulphur fuel oil
MARPOL	International Convention for the Prevention of Pollution from Ships, adopted in 1973 at IMO
MEPC	Marine Environmental Protection Committee, of the IMO
MGO	Marine gasoil
MRV	Mandatory requirements for ships on monitoring, reporting and verification of CO_2 emissions from ships within EU
NM	Nautical mile
NO_X	Nitrogen oxides
REDII	The EU Renewable Energy Directive II, revises RED I and establishes an overall policy for the production and promotion of energy from renewable sources in the EU
SECA	Sulphur emission control area, IMOs denomination of zones where stricter regulations on sulphur emissions from ships apply.
Slip	Unburned methane within engine exhausts
SO_X	Sulphur oxides
TTW	Tank to wheel

1 INTRODUCTION AND BACKGROUND

In 2018, the IMO adopted an initial strategy to reduce and eventually phase out greenhouse gases from the shipping sector. Achieving the goals of reducing emissions from shipping requires the phasing out of fossil fuels. Liquefied natural gas (LNG) has been discussed as a transition fuel and is popular in shipping for environmental and cost reasons. LNG contains less carbon per unit of energy than conventional marine fuels, which means that combustion emits less carbon dioxide. LNG therefore produces lower CO_2 emissions per unit of energy than fossil oil, but far from solves the whole problem.

Renewable liquefied biogas (LBG) can replace LNG as fuel in LNG-powered vessels without any changes on board the vessels. During the last two decades, a growing number of vessels with heavy traffic to and from Swedish ports are able to operate on LNG, and the number is steadily increasing.

This study has therefore been initiated to analyse the conditions for introducing LBG on a large scale in Swedish short sea shipping. The project answers the questions of whether the introduction of LBG on a large scale in shipping in our immediate area can be a reasonable way to phase out fossil fuels from shipping linked to Sweden, what the biggest obstacles to this are, and how much LBG and Liquid Bio methane through electrochemical pathways (e-LBM) that may be available for shipping by 2030 and in the longer term. The same applies internationally, which is why the situation in countries in Sweden's immediate area also have been taken into account.

The proportion of vessels using LNG is growing, both in a Swedish perspective and on a global basis. Lloyd’s Register Marine and University College London have estimated that LNG may account for 5–10% of total fuel use for global shipping by 2030 (Lloyd’s, 2014). Ongoing development seems to prove that these forecasts was correct or even underestimated the development of LNG as a marine fuel.

LNG is popular due to favourable environment and cost reasons. LNG contains very little sulphur, which results in low emissions of sulphur oxides (SO_X) and most marine LNG engines are of a type that also has low emissions of nitrogen oxides (NO_X). These low emissions of SO_X and NO_X make LNG an attractive fuel for ships operating in emission control areas, where ships must comply with stricter air quality standards. LNG has historically been cheaper and will probably continue to be cheaper than MGO and heavy fuel oil, which means that there is an incentive for shipping companies to invest in LNG vessels (Pavlenko et al, 2020). However, during 2021, the price for LNG has increased dramatically and instead become significantly more expensive per energy content than the traditional fossil marine fuels such as MGO (Gasum, 2021). This situation with high LNG prices compared with MGO etc is not expected to last.

Another problem associated with operation on board ships with LNG / LBG is that most of the engines delivered today have problems with unburned methane passing through the engine and being emitted with the exhaust gases, so-called slip (Pavlenko et al, 2020). This slip contributes to GHG emissions and the problem is important to continue working with and applies to operations with both LNG and LBG but has not been the focus of this study. The problem with engines emitting methane slip is not affected if the engine is fuelled by LNG or renewable LBG. Possibilities to decrease methane slip is for example discussed in Winnes (2020).

Extensive use of biofuels in shipping would require significantly higher production volumes and thus an increased supply of sustainable biomass, which is a limiting factor. e-LBM can therefore in the longer term be a solution to the lack of available sustainable biomass because the production of electrofuels is not limited to the same extent as other biofuels by the supply potential for sustainable biomass (Winnes et al, 2019). For e-LBM electricity, water and carbon dioxide are needed.

The benefit of operating vessels with Liquid Bio-Methane (LBM that is synonym to both LBG and e-LBM) on a larger scale instead of, as is the case today with LNG, is large from an environmental and sustainability perspective. The study has produced data that shows the potential for this change, which is expected to lower thresholds for both investing in production capacity and stimulating demand.

The project has been working with the following socio-techno-economic areas:

1. Assessment of available quantities of LBM (LBG and e-LBM) for shipping.
2. Identification of segments and vessel types
3. Economical calculations to assess the price level of LBM
4. Socio-economic benefit
5. Investigate and assess the industry's conditions and attitudes for a transition towards LBM
6. Assess the possibilities to accelerate and contribute to the introduction of LBM in the shipping sector by possible instruments (which can accelerate both willingness to produce and willingness to use).

1.1 METHODOLOGY AND IMPLEMENTATION

The project has used a system perspective where different parameters are compared for different possible solutions with the common goal of using LBM as a fuel in shipping. Emphasis has been placed on shipping to and from Sweden, but also a more comprehensive analyses of the supply of fuel in Europe has been carried out. This is relevant because shipping and the bunker market have a clearly international character. These parameters are:

- Available amount of LBM,
- Cost for production and operation of LBM,
- Socio-economic cost and benefit analysis (through CO_2 equivalents, NO_X & PM and overall estimation of socio-economic damage costs for greenhouse gases and emissions).

1.1.1 Production potential of bio-methane in Sweden

Analysis and mapping of the production potential of bio-methane[1] in Sweden has been assessed through the following sources:

- Previously published reports regarding bio-methane potential from different sources in Sweden
- Environmental permits regarding allowed biogas production at the existing Swedish biogas plants

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[1] A near-pure source of renewable methane produced either by "upgrading" biogas (a process that removes any CO_2 and other contaminants present in the biogas) or through thermo and electrochemical pathways with subsequent methanation.

- Documentation from applications regarding biogas production to the financial support systems of *LBG Drive* and Swedish EPD´s *Klimatklivet*
- Personal contact with owners of biogas plants and energy companies
- Publications about thermo- and electrochemical pathways for production of bio-methane
- Assumptions made by the project co-workers based on previous experience

1.1.2 Demand for Bio-methane in Sweden

Analysis and mapping of the demand of bio-methane in Sweden has been assessed through gathering and analysing statistics from different sources and reports containing relevant forecasts on energy use. Such as:

- SCB (Statistics Sweden), The Swedish Energy Agency
- Communication sent out from specific industries related to their plans for future use of bio-methane in compressed (CBM) and liquid form (LBM) as well as direct contact with industries
- Assessment of data on ships together with ship calls statistics and predictions on new building of ships
- Assessments from truck manufacturers on future sales of different vehicles and which fuels being predicted
- Discussions with the reference group and others, especially ship owners, and their view on switching towards LBM, conditions for such a switch and barriers.

1.1.3 Policy instruments and other means for introduction

An overview and analysis of relevant policy instruments have been done through literature study of:

- Existing policies and policy instruments on EU, national and regional level
- Proposed policies and policy instruments in governmental investigations
- Proposed measures in budget proposition

Not only policies affecting directly LBM in sea transported has been investigated but also polices affecting bio-methane development in general and its use in different sectors and thus its availability for use in sea transport.

1.1.4 Scenario analysis

In the scenario analysis, the supply and demand are being calculated for LBM and CBM from 2021 to 2045, which is visualised in bar graphs for the years 2021, 2030 and 2045. Supply has been distributed as production capacity for LBM and CBM and demand has been distributed among three categories namely industry, road transport and shipping for LBM and CBM. The starting point is the year 2021 for both supply and demand.

The supply in 2021 is based on the current production capacity for LBM and CBM in Sweden. The forecast to 2045 is mainly based on the mapped planned new production capacity projects in Sweden which is shown in section 2.2 below. These projects have received investment support from the climate step which ends in 2026 and are therefore assumed to produce CBM or LBM the year 2026 or earlier. From 2026 onwards we have assumed a percentage increase of production capacity until the year 2045. The exception is Scenario 3b where we have assumed that there will be additional planned projects until the year 2030 and thereafter assumed a percentage increase from 2030 to the year 2045.

The demand in 2021 is based on the current demand for LBM and CBM in Sweden. The forecast to 2045 is mainly based on mapped planned projects in Sweden for each category, which is highlighted in Chapter 3, where an increase in GWh per year until 2045 has been assumed. The demand scenarios are built on data and forecasts within the segments and vessel types using LNG today and the predicted development as well as competing sales in industry and land transportation. The reason behind the three different scenarios presented is different levels of policy development such as support for bio-methane production, internalisation of external costs for emissions and GHG in shipping etc.

1.1.5 LCA

Calculations on the life cycle (LCA) performance of different production pathways for LBM were performed. The first one is estimates calculated in accordance with the emission factors for climate impact calculations from European directive RED II.

Data models of production and use of LBM have also been developed in the project based on academic literature and the commercial life cycle inventory database Ecoinvent. The models were built in the software OpenLCA and built based on the LCA ISO standard ISO14044 and the general guidelines provided by von der Assen et al (2013) and Müller et al (2020).

An overview and analysis of relevant academic LCA literature have been done through literature study of:

- Life cycle assessment studies of electromethane available on Scopus
- Publications about thermo- and electrochemical pathways for production of bio-methane
- Previously published reports regarding the environmental impact form LBM from different sources in Sweden

1.1.6 Cost benefit analysis

Cost and benefit analysis has been performed from the point of view of the shipping company and the transport buyer, respectively. The cost of transporting goods is taken into account, as well as the benefit of switching to biofuels, including socio-economic calculations.

2 PRODUCTION POTENTIAL OF BIO-METHANE IN SWEDEN

2.1 BIOGAS POTENTIAL

There have been several studies from the 80s onwards that have calculated how much biogas can be produced in Sweden via anaerobic digestion from Swedish substrates, based on different forms of assumptions. Table 1 summarises the results from the more recent national studies.

Table 1. Biogas potential estimations from different studies from Swedish substrates in TWh/year. Potential assessments made with no restrictions (total potential), taking technical challenges (technical potential) and market conditions (economic potential) respectively into account.

Study/Reference	Theoretical biogas potential (TWh/yr)	Technical potential (TWh/yr)	Economic potential (TWh/yr)	Boundaries/ Comment
Linne et al (2008)	15.2	10.6		Excludes energy crops
Energimyndigheten (2010)		15.5	3.5	Includes energy crops
WSP (2013)		1.2–9.6		Includes energy crops
Börjesson (2013)		6.2		Excludes energy crops and straw
Börjesson (2013)		6.5		Includes 10 % energy crops
Börjesson et al (2016)		4.5		Value corresponds to increased biogas production potential from the 2014 level from waste and residual products
Ahlgren et al (2017)		4–10		Value only including ILUC free crops and straw[1]
Lönnqvist (2017)			7	Includes ley crops on fallow land (1 TWh, the remaining 6 TWh are waste and residues)
SOU (2019)			14–15	Includes 4–5 TWh of waste and residues as well as 10 TWh of ILUC free crops and agricultural residues.
Börjesson (2021)		9-14 (4-6 from manure & organic residues, 2-4 from straw, 3-4 from biomass from ecological focus areas & unused arable land)		Values correspond to increased supply potential until 2030. Adding biogas production of today gives a total of ~11-16 [2]
		11-19 (4-6 from manure & organic residues, 2-3 from straw and 5-10 from biomass from ecological focus areas & unused arable land)		Values correspond to increased supply potential until 2050. Adding biogas production of today gives a total of ~13-21[2]

[1] ILUC (Indirect Land Use Change) means that increased production of biofuels in one country can lead to the displacement of other agricultural production, which in the long run can lead to a conversion of forest or grazing land to agricultural land elsewhere and thereby cause unwanted indirect greenhouse gas emissions.

[2] Calculation in brackets made by authors of this study, based on actual biogas production of 2020 (Energigas Sverige 2021).

Linné et al (2008) have a clearly stated methodology for assessing national and regional biogas potential. Terminology in Linné et al. (2008) is for the biogas potential; total biogas potential (corresponds approximately to theoretical biogas potential) and total with limitations (corresponds approximately to technical/economic biogas potential, where technical and economic challenges have been taken into account). Competitive uses for the substrates are taken into account in the latter category.

The Swedish Energy Agency (2010) has taken other parameters into account in its assessment of the national biogas potential competing sectors and technical and economic potential. Examples are heating and CHP plants that compete with biogas producers for straw. WSP (2013) has developed three scenarios where conditions vary based on possible future development. Economic growth, technological development and instruments are varied in these scenarios. Börjesson (2010 & 2013) has produced an updated version of Linne et al (2008) where straw is excluded. Börjesson (2016) has since updated the market potential based on WSP (2013) and Börjesson (2013) where the potential is stated as an increased market potential with regard to the current instruments, which corresponds to 4.5 TWh/year compared with existing biogas production in 2014, which gives a market potential of approximately 6.2 TWh/year.

Börjesson (2013) states that the biogas potential from energy crops depends above all on how much cultivation area is available, but also on harvest levels and biogas yield. Here, a biogas potential of 6.5 TWh/year is stated if 10% of the arable area in Sweden is used to grow crops for biogas production.

Ahlgren (2017) states that approximately 4-10 TWh biogas / year could be produced as ILUC free biofuel from arable land. Here, account is taken of grassland from abandoned arable land and arable land and that part of the straw is also used for the production of biogas. Lönnqvist (2017) estimates a practical biogas production potential of 7.2 TWh/year of which 1.4 TWh would come from ley crops on arable land and the rest from waste and residues.

The governmental investigation regarding biogas markets SOU (2019) presents an estimation of 14.1-15 TWh/year based on three previous estimations (Börjesson (2016); Ahlgren et al. (2017), and Lönnqvist (2017).

Börjesson (2021) is an update of Börjesson (2016), where the production potential has been estimated for both year 2030 and 2050. An increase of the potential is assumed from 2030 to 2050 and for biomass suitable for biogas production the increase consists of higher amounts from ecological focus areas and unused arable land. The increase is motivated with increased available areas for such production as well as improved and adapted systems for harvesting this kind of biomass. For example, intermediate and catch crops are mentioned and estimated to increase in order to prevent nutrient leakage in combination with longer growing seasons due to climate change, an increase of cultivation systems promoting high biodiversity and high biomass production and increase of grassland for increased carbon sequestration (for example in cereal growth sequences).

To have some margin to estimated maximum biogas production values in Börjesson (2021) 14 and 19 TWh/year for 2030 and 2050 respectively have been chosen to be used as maximum biogas production values in the current study. These values are somewhat higher than of the earlier national potential studies (see Table 1). If for example adding the result from Börjesson (2013, 2016), where energy crops and straw were excluded, and Ahlgren et al (2017), where only energy crops and straw were included, we achieve a total biogas potential of about 16 GWh/year. However, as clearly stressed in Börjesson (2021), the possible production potential that will be realised is largely due to the development of both national and EU policy and regulations regarding energy, climate and agriculture in the coming years.

The Swedish Environmental Protection Agency forecasts that there will be less amount of manure in the future due to change in amount of production of meat and dairy products and the extent of animals that are indoors in Swedish agriculture (SOU 2021:48). Diminishing amount of manure over time is also considered in Börjesson (2021), but the decreased amount is in the study considered to be compensated by bigger production units making a bigger portion of the manure economically feasible to use for biogas production.

2.1.1 Regional potential

The biogas production potential differs regionally in Sweden, depending on for example population density (i.e. organic waste from households and sludge from wastewater treatment plants), agriculture activity (i.e. manure and residues of crops) and industry that use organic material (i.e. organic residues). To illustrate the regional biogas potential the study of Linné et al (2008), where data was collected and reported for each Swedish county, have been used as a base. The data from Linné et al (2008) have then been actualized and modified in the following way:

- Where local studies dated later than 2008 have been performed, and where the data have taken technical- and economical restrictions into account, this data have replaced the data from Linné et al (2008) for respective substrate category. This applies for the counties of Skåne (Björnsson et al, 2011), Halland (Sandberg et al, 2012), Västra Götaland (Grahn et al, 2020), Västernorrland (Fransson et al, 2013), Västerbotten and Norrbotten (Biofuel Region, 2013). The difference in biogas potential with restrictions for these counties between Linné et al (2008) and the mentioned studies were in total 0.4 TWh/year higher potential in Linné et al (2008), which corresponds to about 0.4 % of the total biogas potential with restrictions according to Linné et al (2008).

- 75 % instead of 60 % of the total biogas potential from food waste from households have been assumed to be available for biogas production in the value for biogas potential with restrictions. This is justified by higher performance in pre-treatment plants and increased population size since the publication of Linné et al (2008).

- 35 % instead of 52 % of the total biogas potential from straw have been assumed to be available for biogas production in the value for biogas potential with restrictions. This have been made according to Ahlgren et al (2017) where 2 TWh/year straw are considered to be available for use outside the agricultural sector.

The result of the regional potential with modified data from Linné et al (2008) is shown in Figure 1. Some of the biogas potential from industries and residual currents couldn´t be reported on a regional basis in Linné et al (2008). This corresponds to 842 and 441 GWh/year for the total biogas potential and the biogas potential with restrictions, respectively, and are shown in a column called “undefined” in Figure 1. Important to note is that energy crops or other biomasses that are not considered to be residues have not been included in the figures. The result can be used as an indication of the variation and the amount of the potential for regional biogas production.

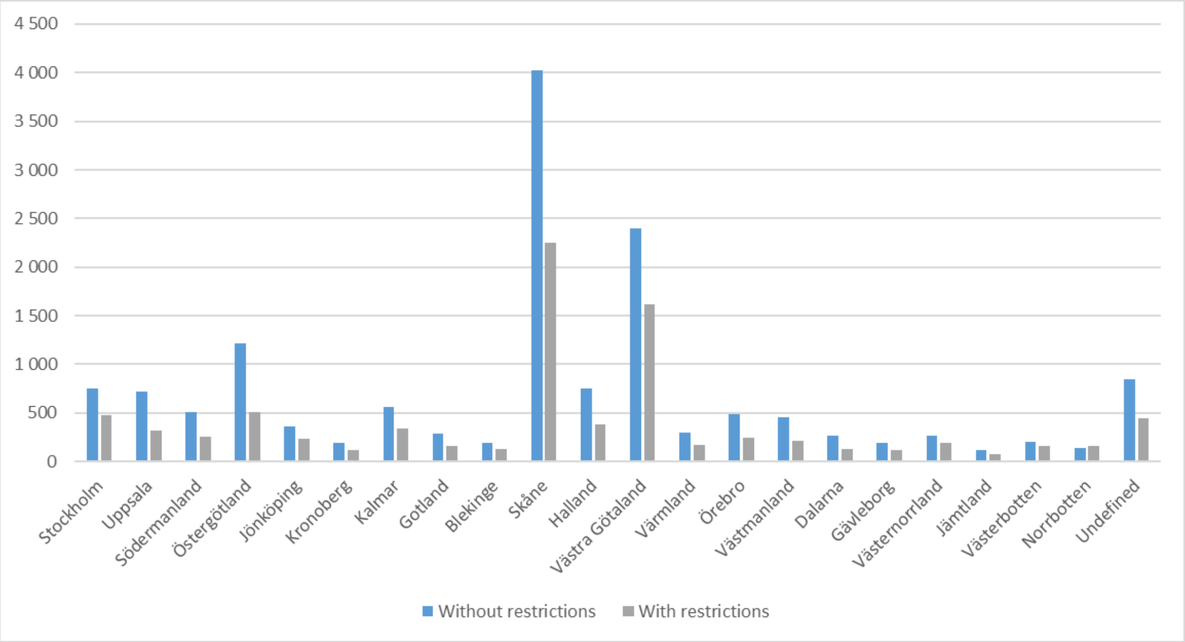

Figure 1. Biogas potential for Swedish counties in GWh/year with and without technical/economic restrictions respectively. Based on Linné et al (2008) with actualized and modified data regarding more recent regional potential studies and general assumptions made regarding availability of food waste from household and straw. Biogas potential from industries and residual currents that of different reasons could not be reported on a regional basis in Linné et al (2008) are shown in the column called "undefined". The data does not include energy crops or other biomasses that are not considered to be residues.

2.2 COMPILATION OF EXISTING AND PLANNED BIOGAS PRODUCTION CAPACITY

A compilation of existing as well as planned biogas production capacity for each county in Sweden has been made. Only biogas plants that have a biogas upgrading unit to produce biogas of vehicle fuel quality have been addressed, meaning that mainly smaller production sites of biogas that lack this facility are not included in the compilation. For existing biogas plants allowed maximum biogas production due to environmental permit or information for the producer have been used to determine the production capacity of each plant. Planned biogas production capacity, both for extended production at an existing biogas plant as well as establishment at new sites, documentation from applications for investment support from the Swedish national financial support systems for sustainable development of "Drive LBG" and "Klimatklivet" organized through The Swedish Energy Agency and The Swedish Environmental Protection Agency respectively have been used along with contacts with national biogas actors.

The existing biogas production capacity has been divided into capacity of compressed biogas (CBG) and liquified biogas (LBG), respectively. For planned biogas production the amount of biogas produced consist in part of biogas plants that change from CBG to LBG production by addition of a liquefaction unit, meaning no effect in total biogas production amount, and in part of establishment of new biogas production sites or extended production at an existing plant meaning a total increase of the national biogas production. Planned projects encountered in the compilation ranges from late 2021 until 2026 for start of operation. The planned projects included in the compilation are thus all rather nearby in time and can be considered likely to be realised due to rather elaborated details about the establishments (see further discussion about the topic in chapter 5).

The result of the compilation shows a total biogas production capacity of about 3.6 TWh/year[2] in Sweden during 2026 (see Figure 2), where 2.1 TWh/year is existing capacity, and 1.5 TWh/year is new capacity. Planned new production consists of about 1.3 TWh/year LBG and 0.2 TWh/year CBG. Except new production facilities of biogas there is also plans of investments for liquefaction of existing CBG-production into LBG, giving a total of 0.5 TWh/year replacement.

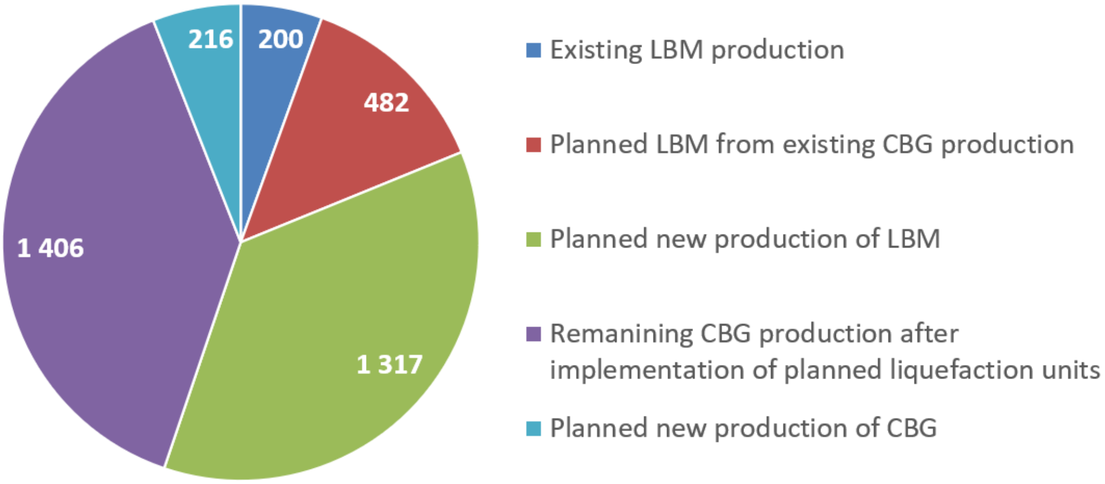

Figure 2. Total existing and planned biogas production capacity from anaerobic digestion in GWh/year. Production capacity divided into existing LBM production, planned new production of CBG and LBM respectively, planned LBM production from existing CBG production and total remaining CBG production after implementation of planned liquefaction units at existing biogas plants.

The existing and planned biogas production capacity differ considerably between different Swedish counties (see Figure 3). The greatest production potential, taking economical- and technical restrictions into account, as well as existing and planned production capacity is found in the counties of Skåne and Västra Götaland. In Skåne, the production capacity is 790 GWh/year, where 425 GWh/year is existing, and 365 GWh/year is planned production capacity.

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[2] The production capacity refers to planned capacity that is expected to be in place 2026 in line with support from Klimatklivet.

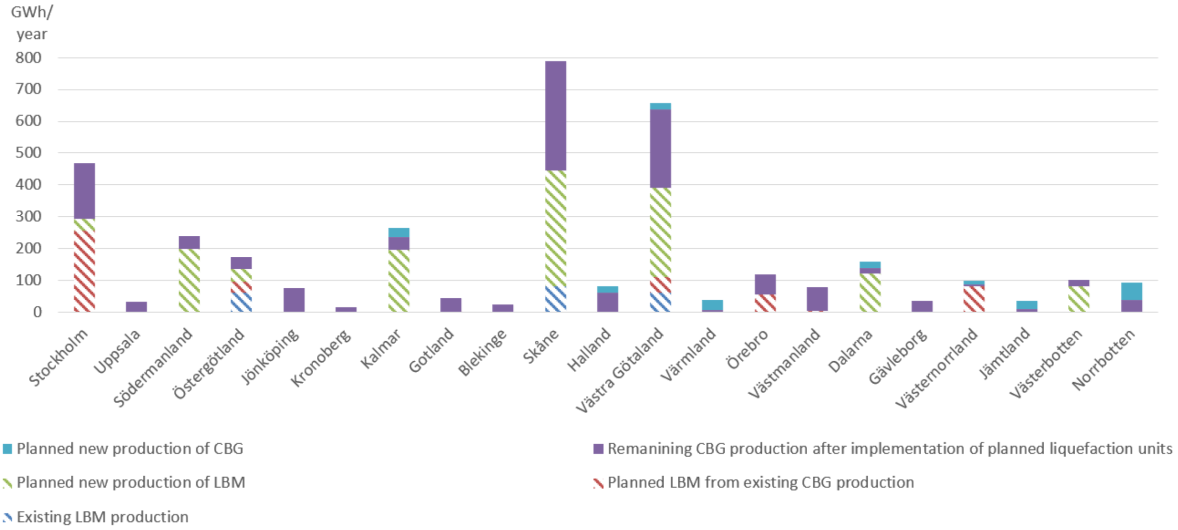


Figure 3. Existing and planned biogas production capacity per county of Sweden in GWh/year. Production capacity divided into existing LBM production, planned new production of CBG and LBM respectively, planned LBM production from existing CBG production and total remaining CBG production after implementation of planned liquefaction units at existing biogas plants. Each pile in the diagram shows the total biogas production capacity (CBG+LBM) in GWh/year per county if all actual planned investments in new production are realized.

The capacity, existing as well as planned, does rather fairly reflect the identified theoretical potential of each county according to values received in the actualized and modified figures from Linné et al (2008) (see chapter 2.1 -Regional potential and Figure 1), in the sense that where the greatest potential is identified also most production capacity are/are going to be installed (see Figure 4).

The theoretical biogas potential, with economical and technical restrictions taken into account and energy crops and other biomasses that are not considered to be residual products excluded, is considered to be about 2 300 GWh/year for the county of Skåne (see chapter 2.1 Regional potential, and Figure 1). For Västra Götaland the production capacity is 656 GWh/year, where 354 GWh/year is existing, and 302 GWh/year is planned production capacity. This can be compared to the theoretical biogas potential, taken restriction into account and no energy crops included, that shows a potential of about 1 600 GWh/year (see chapter 2.1 Regional potential, and Figure 1). According to the theoretical potential with economical and technical restrictions there therefore is another 65 and 59 % more biogas that possibly could be produced for Skåne and Västra Götaland respectively (no energy crops included). Overall, there is a considerable potential for an increased biogas production in many of the Swedish counties (see Figure 4).

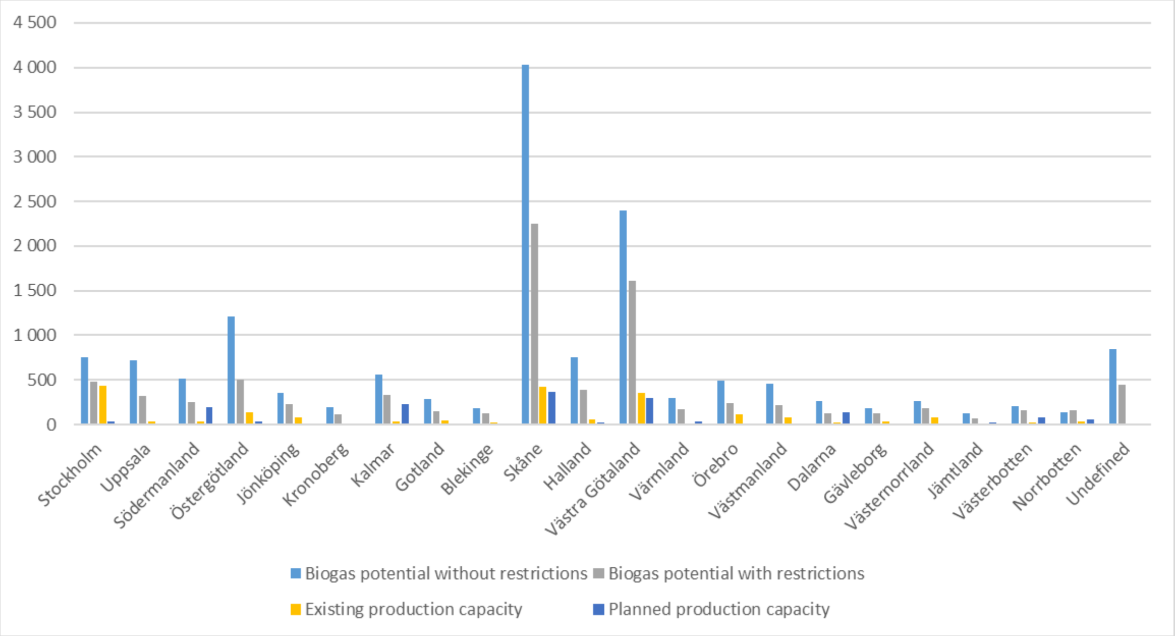


Figure 4. Existing and planned biogas production capacity along with theoretical biogas potential with and without economical- and technical restrictions (Based on Linné et al (2008) with modifications. No energy crops or other biomasses not considered as residual products included.) per county of Sweden in GWh/year.

2.3 THERMO- AND ELECTROCHEMICAL PATHWAYS

Besides the well-established production process of methane through anaerobic digestion at biogas plants there also exists other possible additional future pathways to produce methane in Sweden from biomass/renewable substrates. These processes consist of;

- Production of methane through chemical or biological methanation of CO_2 (from for example CO_2 from raw biogas/anaerobic digestion) and H_2 (from electrolyses of water from renewable electricity production)
- Production of methane through gasification of biomass

According to Jannash A-K (2017), existing biogas production from anaerobic digesters has the potential to increase by 15% to 70% without the addition of additional substrates when electro processes are combined with existing digesters. The range is due to the fact that different substrate combinations give rise to differences in methane and carbon dioxide concentration in the biogas produced. Raw biogas contains between 20-50% CO_2 depending on the type of biomass digested (Chen et al., 2015). On average it is 39.2 % for Swedish conditions (Andersson et al., 2021), which have been used in the calculations.

Theoretically all CO_2 can be combined with hydrogen produced from electrolysis of water in a methanation reactor. However, in the calculation a maximum of 95 respectively 96 % of the CO_2 produced in year 2030 and 2045 have been used. This is based on the:

- assumed total national biogas potential made in this study with technical- and economical restrictions taken into account,
- total production of biogas respectively amount of upgraded vehicle quality biogas that are produced today (Energigas Sverige, 2021),

- assumption that all new production of biogas will be of a plant size making it possible to produce electro-methane as a complement and
- that all existing biogas plants producing biogas of vehicle quality will be able to produce electro-methane as well.

In addition, 95 % availability of the plant has been considered, in accordance with Andersson et al. (2021) and 5 % losses of CO_2 in the chemical methanation (Chauvy, R et al.,2022). With the above-mentioned assumptions 4.7 respectively 6.4 TWh methane per year could be produced from CO_2 from anaerobic digestion plants in year 2030 and 2045. Both chemical and biological methanation is possible, but the chemical methanation process is at present more mature and therefore the potential has been calculated with data from chemical methanation. Despite being immature, biological methanation is considered to be a promising technique in the future. Mainly due to possible easier operation (lower temperature and pressure), more stable (less sensible to impurities in the biogas), catalyst renewal is carried out continuously (only microbial growth is needed), intermittent operation possible (fast start-up) and lower operation costs (Rafrafi et al. 2020).

For methane produced from gasification only syngas originating from gasification of residues of lignocellulosic material from recycling stations (e.g., demolitions and package material including pallets) is included in the estimated production potential due to no, or little, competition of this fraction for other uses. For residues from the forest, it is expected to be a high demand, as well as market competition, for in the future fossil free society. According to the Swedish Environmental Protection Agency (2018) there are 2 million tonnes of residues lignocellulosic material from recycling stations available per year. Based on the residue's lignocellulosic material amounts, that would be corresponding to approximately 3.5 TWh methane production per year (assuming 40 % moisture content and a conversion efficiency of 60 %).

2.4 SUMMARY OF PRODUCTION POTENTIAL

To estimate the total bio-methane production potential in Sweden, the potential from the three different pathways; anaerobic digestion, methanation of excess CO2 from anaerobic digestion and methanation of syngas from gasification, have been added together (see Table 2).

Table 2. Bio-methane production potential for year 2030 and 2045 from anaerobic digestion and methanation of CO_2 from anaerobic digestion- and gasification- plants.

	Bio-methane production potential year 2030 (TWh/year)	Bio-methane production potential year 2045 (TWh/year)	Restrictions regarding technical, economical and sustainability regard
Anaerobic digestion	14	19*	Only substrates originating from manure, organic residues, straw and biomass from ecological focus areas and fallow land are included.
Methanation of CO_2 from anaerobic digestion plants	4.7	6.4	95 and 96 % of the CO_2 from biogas plants is used to produce electromethane in the year 2030 and 2045 respectively, 95 % availability of plant and 5 % losses of CO_2 in the chemical methanation.
Methanation of syngas from gasification plants	3.5	3.5	Only syngas from gasification from residues of lignocellulosic material (e.g., demolitions and package material including pallets) is included.
TOTAL	**22.2**	**28.9**	
* Value refers to year 2050 according to Börjesson (2021). We have assumed the same value for year 2045.			

3 DEMAND FOR BIO-METHANE IN SWEDEN

The information and analyses within this chapter is used to give a picture of the demand at present for methane in compressed and liquid form in the main sectors road transportation, industry and shipping. This information is thereafter used in order to build the demand scenarios in Chapter 5.

3.1 ROAD TRANSPORT

Demand for liquid methane (LBM and LNG) for road transport in Sweden has been reported annually by Statistics Sweden since 2017. Demand for liquid methane increases every year and is expected to be around 0,10 TWh in 2021, where the share of LBM is expected to be around 60 % in 2021, as shown in the table below.

Table 3. LBM and LNG deliveries to road transport in Sweden according to Statistics Sweden (2021).

Year	2017	2018	2019	2020	2021*
LBM [tons]	72	94	781	2 729	6 615
[GWh]**	0.9	1.2	10	35	86
LBM (%)	22	30	47	49	62
LNG [tons]	257	225	892	2 827	3 729
[GWh]**	3.3	2.9	12	37	48
LNG (%)	78	70	53	51	38
Total [tons]	329	318	1 674	5 556	9 894
[GWh]**	4.3	4.1	22	72	130
* Approximated ** Calculated					

To put this in perspective, the energy consumption in Sweden is according to SOU (2021) about 20 TWh/year for the heavy vehicle segment.

Demand for compressed methane (CBG and CNG) in Sweden has been reported annually by Statistics Sweden since 2009. Demand for compressed methane increased until 2013 and has since stabilized where a certain decline can be indicated in 2020 while the share of CBG is expected to be around 95 % in 2020, which shown in Figure 5.

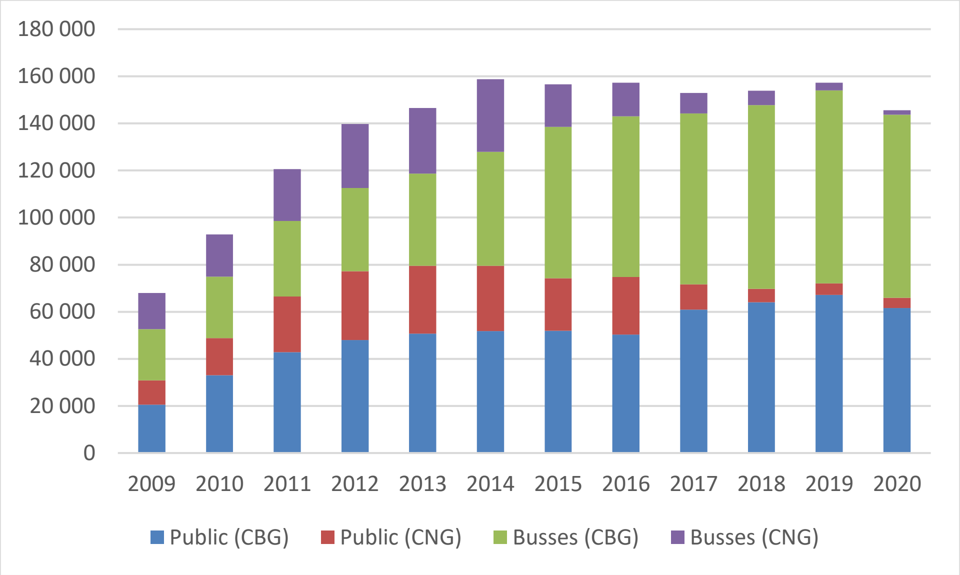


Figure 5. CBG and CNG deliveries in Nm3 to road transport in Sweden according to statistics Sweden (2021).

Recently, the interest in electricity-based drive chains as a core part of fossil-free transportation in urban environments has been steadily increasing, and numerous municipalities have begun a transition from biofuels to electrification in their bus fleets. This has primarily been pursued in inner-city transportation systems thus far, and is apparently accelerating, in turn displacing compressed biogas and other biofuels (Martin et al, 2021). A similar development is also foreseen for passenger cars.

Heavy trucks could run on LBM which is a good alternative for many trucking companies searching for a low carbon fuel alternative. The costs for LNG/LBM fuel with the present costs structure including taxes, subsidiaries etc has made LBM a cost competitive fuel with a good overall cost picture, especially for long haul trucking with high annual truck milage. There has however recently been a change and the historical price relations between methane fuels and diesel fuels now differs with a cost increase on LNG that started mid 2021 when the cost for LNG per energy unit suddenly increased and became significantly higher than the cost for liquid fossil fuels such as diesel (Gasum, 2021).

The LNG/LBM heavy vehicles in Sweden have grown year on year since 2018 and also the growth rate increases year by year. Present sales volumes lay around +100 new heavy trucks per year. Both Scania and Volvo Trucks have a similar message, that over time, electrification and fuel cell solutions will be the major sales part but also LBM and other solutions are expected to have a role to play within the heavy truck segment.

Within this study, we have collected data over registered heavy vehicles in Sweden over the years with LNG/LBM as a fuel and looked through the already granted support from Klimatklivet and DriveLBG. That, together with the present production and sales of LNG/LBM for the time period have been analysed and future demand predictions have been made in this report.

An example of estimated future demand for LBG for heavy trucks is given in SOU (2021) that with an annual new sales share of 20% LBM heavy trucks from year 2021 and onwards, the annual LBM consumption for heavy trucks year 2040 would be approximately 4 TWh. Similar sales and consumption scenarios have been made until 2045 in this report.

3.2 INDUSTRY

The amount of fuel that the industry used in 2019 and 2020 is approximately 81 TWh, of which approximately 33% are fossil fuels. The figure below summarizes the amount of fuel used. (Statistics Sweden, 2021)

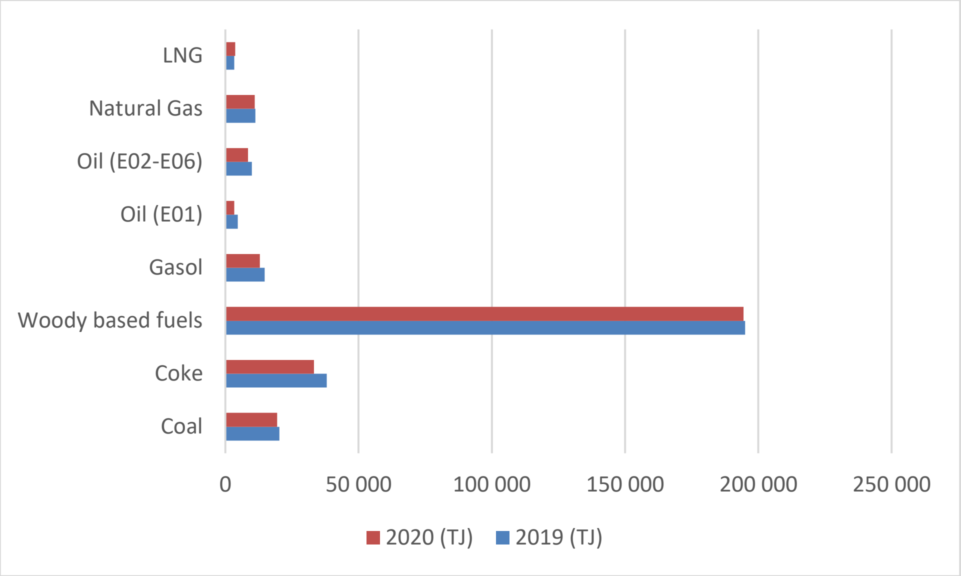


Figure 6. Fuel use in the Swedish industry according to Statistics Sweden (2021).

Fossil fuel use in the industry in Sweden is around 27 TWh as an average of year 2019 and 2020. The fuels that can directly be replaced with LBM are LNG, while natural gas can be replaced with compressed bio-methane. The amount of LNG used in Sweden is approximately 1 TWh and the amount of natural gas used in Sweden is 3 TWh as an average of 2019 and 2020.

Some industries have already started replacing oil, coal and coke with natural gas, LNG or LPG which then can be replaced with bio-methane or LBM. There are also examples of industries that want to replace LPG, oil, coke or coal with natural gas or LNG which then can be replaced with biogas or LBM (Biogas Research Center, 2021, Energigas Sverige, 2021d, Eklund, 2021). Other industries such as Toyota has already replaced fossil fuels with LBM or bio-methane (Östsvenska Handelskammaren, 2021).

Industries, such as the steel industry, have plans to replace fossil fuels with electricity or hydrogen produced from electrolysis of water. Other industries have reviewed the possibility to reform biogas to hydrogen, where Höganäs is one such example (Rise, 2021). On the other hand, Perstorp and several other industrial companies sees the possibility to use the carbon atoms in the biogas in their chemical manufacturing processes (Secher, 2021). All in all, substantial amount of bio-methane potential demand can be seen.

3.3 SHIPPING

This section gives an analysis of which segments and vessel types can most easily be bunkered over time with LBM and these volumes.

In 2021, about 12 % of current newbuilds ordered have alternative fuel systems of which about 6 % being LNG (DNV, 2021b). The mandatory reporting data for all ships within the EU MRV system is available for analyses and within the scope of current report; the MRV database for 2018, 2019 and 2020 has been linked with ship data from the HIS Maritime & Trade Sea-web database. Based on that material, the present and the trend for LNG vessels and their consumption within EU waters have been assessed.

It is a growing trend with vessels delivered with LNG as main fuel onboard and for 2018, 13 vessels were operative, in 2019 the number increased in total to 40 vessels and during 2020 the total number was all in all 49 vessels (LNG carriers excluded as they are assessed being built with LNG as fuel, taken from the cargo transported). These LNG vessels roughly consumed in total 1.3 TWh (2018), 3.2 TWh (2019 and 3.9 TWh (2020). The LNG consumption was calculated to 25 TWh (or approximately 0.8 % of total EU vessel fuel) LNG during 2020 out of approximately totally 470 TWh bunker fuel within EU. Calculated energy consumption per vessel types can be seen in Table 4. These calculations shall be seen as estimates, since the available MRV data do not state which fuel each vessel has actually consumed. We have used the assumption that all vessels with the stated fuel type 1 as LNG also run-on LNG (see Table 5). In reality, a certain part of this fuel will be MGO and other liquid bunker fuels.

Table 4. Total energy consumption per vessel type within EU during 2020. Calculation made by authors of this study, based on based on EU MRV statistics, SeaWeb database on ship information.

Ship type	Total energy [TWh]
Container ship	156
Oil tanker	67
Bulk carrier	53
Ro-pax ship	42
LNG carrier	35
Chemical tanker	34
General cargo ship	22
Ro-ro ship	19
Vehicle carrier	15
Gas carrier	10
Refrigerated cargo carrier	6
Container/ro-ro cargo ship	5
Passenger ship	5
Other ship types	4
Combination carrier	0.4
Grand Total	**471**

Table 5. Total energy consumption per vessel type within EU during 2020 for vessels with Fuel type 1 as LNG. Calculation made by authors of this study, based on based on EU MRV statistics, SeaWeb database on ship information.

Ship type	Total energy [TWh]
LNG carrier	18.9
Gas carrier	2.3
Ro-pax ship	1.5
Oil tanker	0.9
Chemical tanker	0.5
Container ship	0.5
Passenger ship	0.4
General cargo ship	0.1
Other ship types	0.04
Grand Total	**25**

The "Swedish part" of marine fuel in total and LNG in particular is difficult to define. This part can for example be calculated based on fuel bunkered in Sweden or by the consumption of domestic ship movements together with an allocated part of vessel movement between Swedish and foreign ports. The Swedish Environmental Agency annually publish statistics on carbon dioxide emissions that origin from marine fuel bunkered from Swedish suppliers, based on this statistic on annual energy consumption within the transport sector in Sweden managed by the Swedish Energy Agency (Energimyndigheten, 2021), which can be seen in Figure 7. Roughly 25 TWh bunker fuel is being bunkered annually in Sweden. Bunkered volumes vary over time with both development of the marine sector but also with the market conditions for bunkering and how competitive the different bunkering locations are compared to other areas that the vessels pass during their operations. However, the level of 25 TWh bunkered annually in Sweden can be seen as an indicator on total energy demand from the shipping sector in Sweden. If for example 15% of the bunker fuel in a couple of years ahead were related to ships with LNG fuel systems, a bit less than 4 TWh LNG would be the potential to replace with LBM.

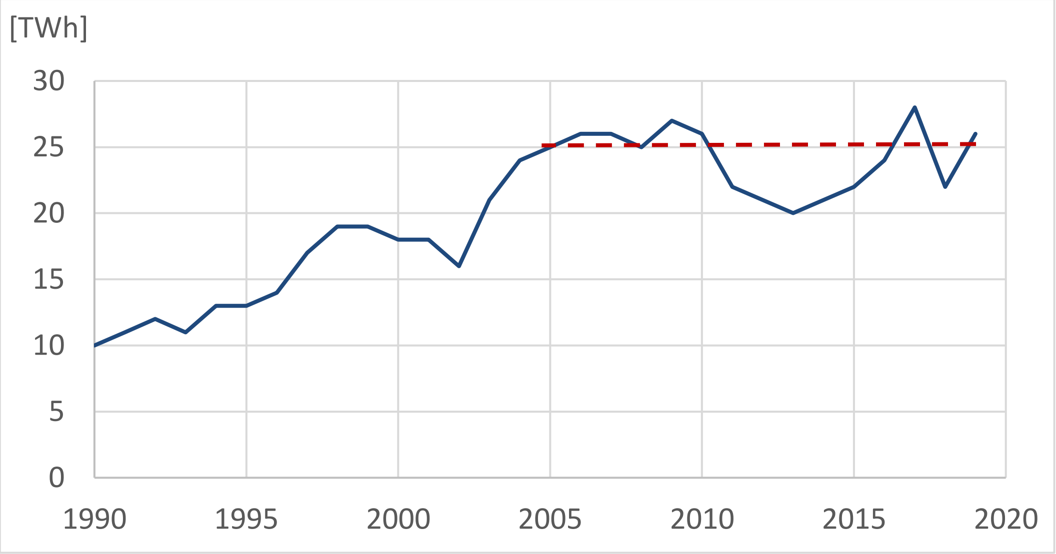
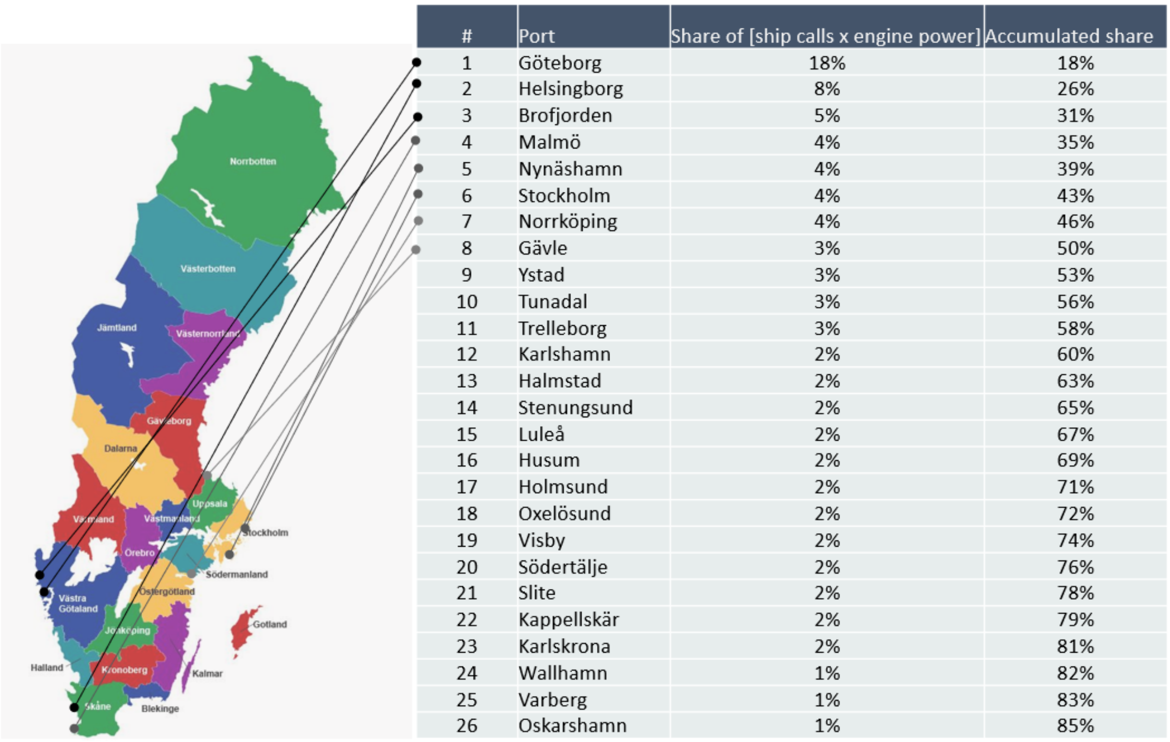


Figure 7. Bunker fuel. Bunkered in Sweden annually during 1990-2019. The red dotted line indicates an approximate level of annually bunkered volumes of 25 TWh during the latest years.

Also, statistics on Swedish port calls have been analysed with the aim to understand if vessels frequently call port areas where also bio-methane production potential exists. Analysis is based on port call statistics (Swedish Maritime Administration, 2021) for year 2020 merged with vessel information from SeaWeb database (2021). In order to understand where the largest need for bunker potentially exists in relation to geography, the sum of installed engine power in kW during year 2000 (for the ships), for each port has been calculated which is shown in Figure 8. The port areas can be compared with the assessed potential for biogas production in section *2.1.1 Regional potential*, shown in Figure 4. There is for example a good match between the highest potential for biogas production in Skåne, Västra Götaland and Östergötland and the highest dense ports Göteborg, Helsingborg, Brofjorden, Malmö, Nynäshamn and Stockholm which is shown in Figure 8.



#	Port	Share of [ship calls x engine power]	Accumulated share
1	Göteborg	18%	18%
2	Helsingborg	8%	26%
3	Brofjorden	5%	31%
4	Malmö	4%	35%
5	Nynäshamn	4%	39%
6	Stockholm	4%	43%
7	Norrköping	4%	46%
8	Gävle	3%	50%
9	Ystad	3%	53%
10	Tunadal	3%	56%
11	Trelleborg	3%	58%
12	Karlshamn	2%	60%
13	Halmstad	2%	63%
14	Stenungsund	2%	65%
15	Luleå	2%	67%
16	Husum	2%	69%
17	Holmsund	2%	71%
18	Oxelösund	2%	72%
19	Visby	2%	74%
20	Södertälje	2%	76%
21	Slite	2%	78%
22	Kappellskär	2%	79%
23	Karlskrona	2%	81%
24	Wallhamn	1%	82%
25	Varberg	1%	83%
26	Oskarshamn	1%	85%

Figure 8. The list shows the share of total annual sum of port call for vessels multiplied with the installed engine capacity (power) for the specific ship during 2020.

4 POLICY INSTRUMENTS AND OTHER MEANS FOR INTRODUCTION OF LBM IN SHIPPING

4.1 POLICY INSTRUMENTS ON A NATIONAL LEVEL

The bio-methane development in the Swedish transport sector has been driven by a combination of political instruments at a regional, national and EU level (Lönnqvist 2017). These include fuel taxes, investment aid for production facilities, investment aid for distribution infrastructure, and aid for the purchase of gas vehicles, often governed by EU regulations.

The fuel tax consists of energy and carbon dioxide taxes and constitutes a significant part of the price at pump for fossil fuels. Thus, the tax can be said to facilitate for renewable fuels, even if EU overcompensation rules place restrictions on this (ibid). Investment support such as LIP (Local investment programs) and KLIMP (Climate investment program) have facilitated investments in bio-methane production and since 2015 there is an opportunity to apply for support via Klimatklivet. Support has also been directed at investments in distribution infrastructure as a complement to the so-called the pump law which mainly favoured ethanol infrastructure (ibid).

However, the low predictability of the various instruments initiated may have been unfavourable for the bio-methane development. The policy flora that affects biofuels in general and bio-methane in particular is changing. Important changes that are underway are described below.

4.1.1 State public investigations

Three Swedish state public investigations have been identified as having particular relevance for bio-methane development:

- Biogas market investigation (SOU 2019:63)
- Governmental investigation regarding phase out of fossil transportation fuels (SOU 2021:48)
- Road to fossil-independent agriculture (SOU 2021:67)

The Biogas market investigation (SOU 2019:63) proposes many measures to support bio-methane development. Most notably are a production subsidy and a production target. The production subsidy would be directed at Swedish-produced bio-methane and may be implemented instead of or in addition to tax exemption. The production target is set at 10 TWh bio-methane/year produced in Sweden by 2030. The target may be compared to the current production level of approximately 2 TWh/year. Most of the bio-methane to be produced is seen to come from anaerobic digestion (7 TWh/year) and the rest from gasification or electrochemical pathways (3 TWh/year) (SOU 2019:63). The price of LBM for shipping in Sweden could decrease compared to the current levels as a result of the production support. Shipping fuel is already tax-exempted and the combination with production support may make it more attractive to use LBM in shipping.

The production support in the state public investigation is divided in three: production, upgrading and liquefaction. In the budget approved by the Swedish parliament November 24th, 2021 a production support is included. The suggested production support would amount 500 million SEK during 2022 and 700 million SEK per year during 2023 and 2024. An evaluation or control station would be done 2024. The support level for 2022 would correspond to 0.25 SEK/kWh.[3] Although the design of the support is not clear yet (December 2021) it appears be directed directly to biogas production (Parliament of Sweden 2021). Thus, the division in production, upgrading and liquefaction, as proposed in the Biogas market investigation (SOU 2019:63), would not be realised. The support is proposed to last until 2040 and would thus be long term and predictable.

The governmental investigation regarding phase out of fossil transportation fuels[4] proposes to phase out fossil fuels from road transport and non-road machinery through decreased transport work, strongly increased electrification, and an increased use of biofuels. This may be achieved through a ban on passenger cars that run on gasoline and diesel. Thus, biofuels would then be available for non-road machinery, aviation and sea transport. In the short term this may be negative for certain biofuel markets, e.g. bio-methane in passenger cars, if sales of such vehicles are to be replaced with electric vehicles by 2030.

The investigation foresees an increased use of biofuels in transport by 2030 and later a decrease. Heavy transport may be difficult to electrify and may thus require biofuels. If so, it is more feasible to introduce LBM in this vehicle fleet compared to other types of vehicles. The investigation evaluates a possible increase of the bonus to environmentally friendly trucks and working machines. It also evaluates if it may be expanded to other vehicles. The investigation also suggests to phase-out fossil fuel tax-refund for working machines in agriculture and forestry (same as the investigation regarding a non-fossil dependent agriculture).

Furthermore, the investigation states that Sweden should push for the shipping sector to be included in the ETS (which would be very positive for renewables and LBM). The investigation states that Sweden should work for that the energy tax directive is revised so that the possibility to give tax exemptions for domestic sea and light transport is removed and the obligation to give tax exemption for international flight and sea transport is removed (which would be very positive for renewables and LBM).

The governmental investigation of an agriculture independent of fossil fuels[5] suggest that the support to biogas production from stable manure[6] is prolonged just as the above-described investigation does. The investigation proposes several other measures that may be positive for Swedish bio-methane development: subsidies to bio-methane and biofertilizer production, tax on imported mineral fertilizer, phase out tax refund for fossil fuels in agriculture, also, premiums to biofuels other than bio-methane. However, the document discusses that there are no suitable working machines on the market that runs on bio-methane and bio-methane is in this context discussed together with hydrogen and electricity.

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[3] Assuming an equal distribution over the existing production of ap. 2 TWh (excl. landfill gas).

[4] Swedish: Utfasningsutredningen. (SOU 2021:48)

[5] Swedish: betänkande av utredningen om fossiloberoende jordbruk. (SOU 2021:67)

[6] Swedish: stödet till produktion av biogas från stallgödsel

Table 6. Main proposals of three governmental investigations with focus on their consequences for bio-methane.

Proposal	Concrete proposal	Biogas in general	LBM sea transport
SOU 2019:63			
Production target	+	+	0
Production support	+	+	0
Support to upgrading of bio-methane	+	+	0
Support to liquefaction of bio-methane	+	+	+
SOU 2021:48			
Use electrification in road transport and make biofuels available for sea transport, work machines and aviation	0	0/-	+
Anticipates an increased use of biofuels by 2030 and later a decrease	-	+	0
Discusses difficulties to electrify heavy transport	-	+	0
Evaluate bonus for environmentally friendly trucks and work machines	0	+	0
Phase-out fossil fuel tax refund in agriculture	+	+	0
Sweden should push in EU for including sea transport in ETS	+	+	+
Sweden should push in EU for changing energy tax directive removing tax exemption for fossil fuels in sea transport and aviation.	+	+	+
SOU 2021:67			
Direct subsidies to bio-methane production	+	+	0
Direct subsidies to biofertilizer production	+	+	0
Tax on imported mineral fertilizers	+	+	0
Phase out tax refund on fossil fuels in agriculture	+	+	0
States that there are no non road mobile machines suitable for bio-methane on the market	-	-	0

4.2 INTERNATIONAL POLICY INSTRUMENTS

Although there are no policy instruments on a global level that directly targets shipping, numerous interventions are discussed among the Marine Environment Protection Committee (MEPC), the International Maritime Organization's (IMO) committee for environmental protection. The IMO has adopted an initial climate strategy as a step towards their target of reducing green-house gas emissions (GHGs) by 50 % in 2050 compared to 2008 (IMO 2018a). In this climate strategy, multiple measures are proposed, divided into short-term, medium-term and long-term actions according to the following intervals (IMO 2018a):

- Candidate short-term measures have a planned implementation between 2018 and 2023, if accepted. Examples of such measures are incentives for early adapters, analysing the use of speed optimisation and reduction, encouraging the development and update of national action plans, the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) who both imply improvements in energy efficiency among new and existing ships

- Candidate mid-term measures have a planned implementation between 2023 and 2030 if accepted. Examples of such measures are new or innovative reduction mechanisms to incentivise GHG reductions, an implementation programme for low-carbon and zero-carbon fuels and operational energy efficiency measures for both new and existing ships

- Candidate long-term measures have a planned implementation beyond 2030. Examples of such measures are facilitating the adoption of new or innovative emission reduction targets and pursuing the development and supply of fossil-free or zero-carbon fuels to promote decarbonisation of the shipping sector in the second half of the century.

Some of the short-term proposed measures concerning energy efficiency, such as the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), are already in force. Due their primary focus on energy efficiency, the measures have indirect effects on GHG emissions. Thus, additional short-term measures were adopted at the 75th session of the MEPC, such as the Energy Efficiency for Existing Ships Index (EEXI), improvements in the Ship Energy Efficiency Management Plan, an operational Carbon Intensity Indicator (CII) and a classification tool (MEPC 76/7/2 - IMO, 2021). Technical and operational measures related to the design of the Carbon Intensity Indicator (CII), Energy Efficiency for Existing Ships Index (EEXI), and Ship Energy Efficiency Management Plan (SEEMP) was adopted at the 76th MEPC meeting in June 2021. The aim of the measures is to decrease the GHG emissions per unit of transport work by 40 % until 2030. At the 77th MEPC meeting in November 2021 it was agreed to initiate the revision of the Initial IMO Strategy on Reduction of GHG Emissions, to be finalized in 2023 (DNV, 2021d).

Multiple market-based and regulatory measures are submitted to the MEPC by its member states and non-governmental organisations (NGOs) as to promote achieving the adopted target for 2050. The discussion concerning the suggested measures are encouraged to be completed as soon as possible, but no later than 2023. Discussions regarding the initial climate strategy are further encouraged to be processed within the same timeframe (MEPC 75/18, in 7.71.41 and 7.71.46 – IMO, 2020). As a part of the general discussions, several suggestions have been submitted within IMO/MEPC. Among them are carbon price mechanisms, levies for bunker fuels, emission trading systems and regulated GHG emissions from fuels. Scope and ambition vary throughout the propositions, and some are described in less detail than others. Among them is the emissions trading system presented in the Norwegian submission (2021) which is similar to the layout in the Norwegian submission from 2010 (60/4/22 2010) and the German submission from 2011(63/5/9). Emission reductions both within and outside the sector could be included in the Norwegian submission from 2010. A gradual implementation was suggested for this system, with the long-term goal of including all emissions in the auctions. The most notable difference in the system suggested by Germany in 2011 is that all emissions would be included already in the initial scope of the system, but with a more generous boundary in the beginning. A review performed by a working group established by MEPC (GHG-WG 3/3/7), concluded that the administration costs only comprise a fraction of the total costs of an ETS and that they are alike the administrative costs of other market-based mechanisms if they require monitoring and supervision of ships and reporting on emissions and/or fuel consumption.

Similar to the EU ETS (where considered revisions are described in 4.2.3), there are several regional carbon trading systems in China and a pilot for a nation-wide system was initialised in February 2021. The price of emissions within this trading system is thus far unknown (Ministry of Ecology and Environment, 2021). This system might be expanded to further include shipping (SPLASH247, 2021).

Along with an expansion to include shipping in the EU ETS, another initiative to regulate emissions from shipping is under development by the Commission. The initiative is called FuelEU Maritime[7] and is one of many measures with the aim to achieve carbon neutrality in the EU by 2050. Its purpose is to promote the transition to alternative fuels with low or zero GHG emissions. The FuelEU Maritime is part of the FitFor55 package (mentioned in section 4.2.1), in which the Energy Taxation Directive (2003/96/eg) is also included, which in turn affects how marine fuels could be taxed.

The revision of 2014/94/EU[8] is another instrument affecting the conditions for the market penetration of LBM. The fuels included in the directive are liquid biofuels, electro-fuels, so-called "decarbonised gas" (including liquefied biogas and electro-methane) and liquid fuels such as ammonia and methane that are produced from hydrogen. The directive promotes a life-cycle perspective (well-to-wake) and includes methane-slip. Moreover, it includes the ships' travel time and the duration of their time in a harbour. Tail-pipe emissions are also highlighted. The following concrete items are additionally investigated:

- Support measures aiming at boosting market uptake of sustainable alternative fuels (e.g. facilitating access to funding, differentiation of port fees, etc.);
- Prescriptive requirements on blending/definition of the share of sustainable alternative fuels and/or shoreside electricity to be used by ships in operation and at berth;
- Goal-based performance requirements on the carbon-intensity of energy used in marine operations and at berth, not prescribing the type of fuels to be used.

4.2.1 EU - Fit for 55

Currently a policy package – Fit for 55 – is being negotiated that affects EU policies. The Fit for 55 package aims for a 55 % reduction of GHG by 2030 compared to 1990.

Fit for 55 will revise the entire EU 2030 climate and energy framework. The policy package aims at achieving the goals of the climate law that was launched in the EU green deal, i.e. a 55 % net reduction of GHG compared to 1990 level and climate neutrality by 2050.

The most notable and relevant proposed changes for LBM in sea transport (Energigas Sverige, 2021b):

- Include sea transport in ETS. Starting gradually 2023 and fully phased in by 2026.
- Ships above 5000 gross ton are included.
- Includes emissions from ships travelling within EU and 50% of voyages to/from EU and third countries.
- Will continue to count emissions from biofuels as zero.

The fact that emissions from biofuels within the ETS system are counted as zero while emissions from passenger cars and light duty vehicles are counted the same way as fossil fuels is perceived as

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[7] CO2 emissions from shipping – encouraging the use of low-carbon fuels (europa.eu), 2021-04-14.

[8] EUR-Lex - 32014L0094 - EN - EUR-Lex (europa.eu)

a contradiction by e.g. Energigas Sverige (ibid). However, it may also be seen as a way to steer the usage of biofuels from passenger cars to other sectors, in line with the reasoning of the Swedish Governmental investigation regarding phase out of fossil transportation fuels (SOU 2021:48). Thus, giving priority to use biofuels in sectors that are more difficult to electrify. This may be positive for the availability of LBM in sea transport.

The package also proposes a revision of the energy tax directive (ETD) which implies minimum taxes for different fuels. In brief, the revised ETD proposes four different categories of fuels each with a certain minimum tax. Category one is for fossil fuel implying the highest tax level. Category two is for so called “transition fuels” such as natural gas. Biogas is placed in category four implying the lowest tax level (ibid). Thus, the revision of ETD will give natural gas a better status as a transitional fuel but not as attractive as biogas (bio-methane). More importantly, the revision would end the tax exemption for fuels in sea transport (DNV, 2021c).

The fit for 55 also includes a revision of alternative fuels infrastructure regulation. This revision would mean that ports in the TEN-T[9] core network must supply shore side electricity by 2030 and LNG by 2025 for passenger- and container ships.

The renewable energy directive (RED II) is also suggested to be revised within the Fit for 55 package. The target share for renewable energy is increased from 32 % to 40 % by 2030 and the targets for transport are reformulated so that they focus on emissions reductions rather than share of renewables.

4.2.2 EU - CEEAG

The Climate, Energy and Environmental Aid Guidelines (CEEAG) regulates the state aid that may be given to environmental protection and energy. CEEAG has a tail pipe focus (as opposed to a LCA focus) and, as a consequence, biogas and other transport biofuels will not be able to maintain their tax exemption that they currently enjoy in Sweden. This is criticized by e.g. Energigas Sverige, 2021b. It may however signify that more LBM is available for sea transport as discussed in section 4.2.1 above.

4.2.3 The EU Emissions Trading System (EU ETS)

On an EU level, instruments are under development that aim to affect GHG emissions from shipping and are likely to be implemented before any measures are realised on a global level (Worldbank, 2020) [10].

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[9] The Trans-European Transport Network (TEN-T) policy addresses the implementation and development of a Europe-wide network of railway lines, roads, inland waterways, maritime shipping routes, ports, airports and railroad terminals. See https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_en

[10] China's emissions trading system will be largest when operational.

Presently, the EU Emissions Trading System (ETS) includes land-based energy-intensive industry and EU-bound aviation and is thus the most extensive carbon pricing mechanism in the world[11] (Worldbank, 2020). The EU ETS is proposed to further expand and to be gradually implemented for shipping as from 2023. The final design of the implementation is, not yet finally established, but expected to be implemented during 2023-2026.

There are important aspects to consider for the implementation of the EU ETS in shipping: the geographic extent, the regulated entity (i.e., who should report and pay), what GHGs should be included, what ships should be included and whether (and if yes, when) an innovation fund should be implemented. The different design parameters are presented in Table 7. Moreover, the price of the emissions allowances affect the results of implementing EU ETS in shipping (Zetterberg et al, 2021).

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[11] China's emissions trading system will be largest when operational.

Table 7. Overview of design aspects of implementing the EU ETS for shipping as proposed by the European Commission. Based on Zetterberg et al. (2021) and updated in line with European Comission (2021) proposal on implementation.

Geographical coverage, 4 options of which option c has been proposed.	a) Internal-EU: Ship emissions within and between EU/EEA member states. b) All international: Option (a) plus journeys from EU/EEA ports to the first port of call outside the EU/EEA and journeys to EU/EEA port from the last port of call outside the EU/EEA **c) Part of international: Option (a) plus 50 % journeys from EU/EEA ports to the first port of call outside the EU/EEA and 50 % of journeys to EU/EEA port from the last port of call outside the EU/EEA** d) Internal-EU + all inbound journeys: Ship emissions within and between EU/EEA member states plus journeys to EU/EEA ports from the last port of call outside the EU/EEA
Regulated entity, 4 options of which the **shipping company** is suggested to be the responsible part*	Ship owner, ship operator, transport buyer or fuel supplier
Allowance allocation mechanism, 4 options of which option a has been proposed.	**a) Auctioning** b) Grandfathering (emission rights free of charge based on historical emissions) c) Benchmarking, based on output, for instance ton-km or passenger-km (possibly one benchmark per sub-sector) d) A mix of (a), (b) and (c)
Included greenhouse gases, 1 option	CO_2
Covered ship categories, 1 option	Covered: Ships above 5 000 gross tonnage Voyages for transporting cargo or passengers for commercial purpose Container ships, bulkers, general cargo ships, ro-ro, tankers and ferry boats NOT COVERED: Ships below 5 000 gross tonnage Voyages for purposes other than transporting cargo or passengers for commercial purpose e.g., fishing ships, war ships, wooden ships and ships not propelled by mechanical means
Time frame of implementation	Incremental implementation from 2023 (Energigas Sverige 2021)

* In line with European Commission (2021): *The person or organisation responsible for the compliance with the EU ETS should be the shipping company, defined as the shipowner or any other organisation or person, such as the manager or the bareboat charterer, that has assumed the responsibility for the operation of the ship from the shipowner and that, on assuming such responsibility, has agreed to take over all the duties and responsibilities imposed by the International Management Code for the Safe Operation of Ships and for Pollution Prevention.*

Recently the Swedish Environmental Protection Agency (Naturvårdsverket 2021) has announced changes regarding in relation to EU-ETS and the possibility to purchase biogas through the natural gas pipeline. Thus, it is possible to purchase biogas produced in one location/country and extract the equivalent amount of gas in another location/country and count this as biogas within the EU-ETS system.

4.2.4 Current debate

Currently Fit for 55 is being discussed and negotiated by the institutions in EU as described above. Other suggested changes in the EU policy framework concerns General Block Exemption Regulation (GBER), among other issues. The regulations would be changed so that the size of biogas plants that may receive state aid is decreased. Currently it is allowed to support plants that have a capacity smaller than a) 50 000 tons per year (production volume[12]) if biogas is used as vehicle fuel or 500 kW (biogas production) if used for other purposes. This limit may be reduced to 400 kW regardless of purpose if the discussed changes is realized (Energigas Sverige 2021c).

Other changes discussed in GBER are based on a tail pipe perspective where emissions and greenhouse gases from fuel production not being accounted for, thus a disadvantage for biogas solutions, including LBM. The suggested changes in particular and the tail pipe perspective in general is strongly criticized by e.g., Energigas Sverige (ibid).

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[12] 50 000 tons of LBM equals around 650 GWh per year.

5 SCENARIOS FOR BIO-METHANE SUPPLY AND DEMAND

Supply and demand for bio-methane are to some extent dependent on each other's development because supply does not increase if there is no demand and vice versa. Interaction is required in several areas to increase supply and demand where there may be barriers that hinder development. For example, Energiforsk (2021) states that the biggest barriers to increasing supply for hydrogen, electricity and bio-methane are institutional, regulatory, and societal barriers and that there are also financial and technical barriers that can hinder development, while regulatory and financial are the biggest barriers to bio-methane.

The scenarios for demand presented in this report builds upon data analysis of collected data and information as well as earlier studies. The absolute consumption levels of LBM in heavy trucks, within shipping etc over time, in the three demand scenarios presented in this study shall be seen as possible outcomes depending on the conditions described for each scenario.

5.1 PRODUCTION CAPACITY (SUPPLY)

Scenarios for production capacity are based on how much bio-methane that can be produced from plants that produce bio-methane via digestion and electrochemical pathways, either as LBM or compressed CBM.

5.1.1 Scenario 1

Scenario 1 is assumed to be the current situation in Sweden with tax exemption for bio-methane as CBM or LBM used in road transport and industry as well as production support for bio-methane produced from manure. The current situation is not considered to change, which means that the economic conditions for biogas production do not change, which in turn means that biogas production in Sweden is not expected to increase. It’s assumed that Electrochemical pathways (e-CBM and e-LBM) are not developed.

5.1.2 Scenario 2

Scenario 2 assumes that a production support scheme is introduced for the production of bio-methane regardless of area of use, which means that production is expected to increase until 2045. e-LBM that uses carbon dioxide separated from biogas together with hydrogen is also included where it’s assumed that they are constructed close by existing biogas plant.

5.1.3 Scenario 3

Scenario 3a and 3b assumes that production support scheme is introduced for the production of bio-methane regardless of area of use and that the economic conditions through effects from other policy’s will be even better than scenarios 1 and 2. e-CBM and e-LBM that uses carbon dioxide separated from biogas together with hydrogen is also included where it’s assumed that they are constructed close by existing biogas plant. Regulatory issues that delay the permit process for bio-methane facilities is shortened which means that more plants could be built each year in order to increase the production capacity. It’s assumed that the regulatory and financial obstacles is handled which means that the production capacity is expected to increase significantly until 2045

5.2 DEMAND FROM DIFFERENT SECTOR

Demand, as potential within earlier studies, has to a large extent been expected to come from road transport (Hjort et al, 2019). Reason is mainly that with current market conditions, LBM produced for shipping will come with a much higher sales price compared with fossil alternatives (LNG), which is also reflected in the fact that total transport costs can increase at levels of 40 % (Winnes et al, 2019) switching from LNG to LBM. However, a change within the cost structure and competitiveness of renewable fuels within the shipping sector has just begun which likely will change the whole picture (see section *4. Policy instruments and other means for introduction of LBM in shipping*).

There are studies that forecast relatively high demand of bio-methane in Sweden and others that show a more modest demand depending on the conditions that are assumed. For example, Energiforsk (2021) forecasts that the demand for natural gas and bio-methane may be around 12-20 TWh 2045 for the transport sector and 2-8 TWh 2045 from industry, half of which is imported. Another example is SWECO (2021), which forecasts a slowly growing demand of approximately 2-3 TWh from the transport sector of which approximately 0.4 TWh would come from shipping during 2045 depending on the degree of electrification.

The scenarios that are built within this study consider the Swedish market and when it comes to shipping the demand for vessels bunkering in Sweden. The starting point for scenarios present consumption of LBM and CBM.

The low and conservative scenario is mainly based on the assumption that limited support for biogas production is implemented and that LBM, in general, remain too expensive for the shipping sector. The moderate expansion scenario assumes that the domestic bio-methane production continues to increase with some support via incentives and that the industry that already has expressed interest in bio-methane continues to increase and that the shipping sector that has shown interest already in LBM find ways to finance the switch also with support from the incentives now under discussion such as ETS etc. The expansive scenario reflects a strong future focus from society to make use of the bio-methane potential that is shown and discussed in section *2. Production potential of bio-methane in Sweden*. The three scenarios for demand are further described below.

5.2.1 Low and conservative scenario

The reason behind the low and conservative scenario is to show a possible scenario for how a limited increase in Swedish biogas production can be shared between the sectors heavy trucks, CBG vehicles, shipping, industry and other. The scenario is mainly based on the assumption that limited support for biogas production is implemented and that LBM, in general, remain too expensive for the shipping sector. It is also assumed in the scenario that the demand for CBG in the light vehicles sector will continue to decrease. The already started demand within the heavy truck sector is assumed to continue until 2030 driven by sales of new heavy trucks. After 2030 it is assumed that sales of new heavy trucks will be all battery-electrical or fuelled with hydrogen. The demand in the industry and others is just assumed to remain at today’s levels.

5.2.2 Moderate expansion scenario

The reason behind the moderate expansion scenario is that production of CBG and LBM continue to grow driven by incentives with finance support for new plants but also implementation and continuation of production support such as the recently decided governmental support. Also, the import of biogas is assumed to continue. The increase of the demand is driven by similar reasons in the different sectors such as the possibility to meet decarbonisation targets, costs for emission trading allowances for replaced fossil fuels and similar. But demand will also come from the need to produce hydrogen where biogas can be a solution for sites where availability of electricity is a scarcity or just a competitive source for hydrogen production. Within shipping, the demand of LBM is driven by reasons such as the strong will to decarbonise shipping that major Swedish shipping companies, today using or planning to build LNG ships, has expressed in direct dialogue with the project team of this report. The increase of LBM in shipping will also be supported by the cost reduction of the fuel switch cost when shipping has been implemented into the European Emission Trading scheme (see 4.2.3).

It is also assumed in the moderate scenario that the domestic biogas production continues to increase with some support via incentives and that the industry that already has expressed interest in biogas continues to increase and that the shipping sector that has shown interest already in LBM find ways to finance the switch also with support from the incentives now under discussion such as ETS etc.

5.2.3 Expansive scenario

The reason behind the expansive scenario reflects a strong future focus from society to make use of the biogas potential that is shown and discussed in section *2*. It is however not assumed that the full theoretical potential to produce up to around 30 TWh of LBM during 2045. Instead, a production of approximately half of that potential is assumed to be materialised driven by strong incentives implemented from society for building production capacity and supporting production. Also, a strong will and need within all sectors to limit greenhouse gases drives the demand for bio-methane. In addition, the scenario is based on the assumption that all the sectors, including shipping will be forced to meet even stronger regulations and policies such as higher costs for GHG emissions as well as strict duties to reduce.

5.3 SCENARIOS IN FIGURES

Based on the information gathered and analysed in relation to present and planned production and demand of bio-methane, different scenarios have been built based also on the assumptions described for the production and demand scenarios respectively (see section 5.1 and 5.2)

5.3.1 Supply scenarios

The supply scenarios described in section 5.1 is shown below for year 2021, 2030 and 2045 respectively.

2021

Year 2021 is the starting value and corresponds to the production capacity from existing plants in Sweden. The production capacity for all scenarios is equal and is approximately 1 900 GWh for CBM and approximately 200 GWh for LBM facilities, while there is no production capacity for the electrochemical routes, which in total corresponds to a production capacity of 2 100 GWh / year. Figure 9 below shows the scenarios which for 2021 all show the same production capacity.

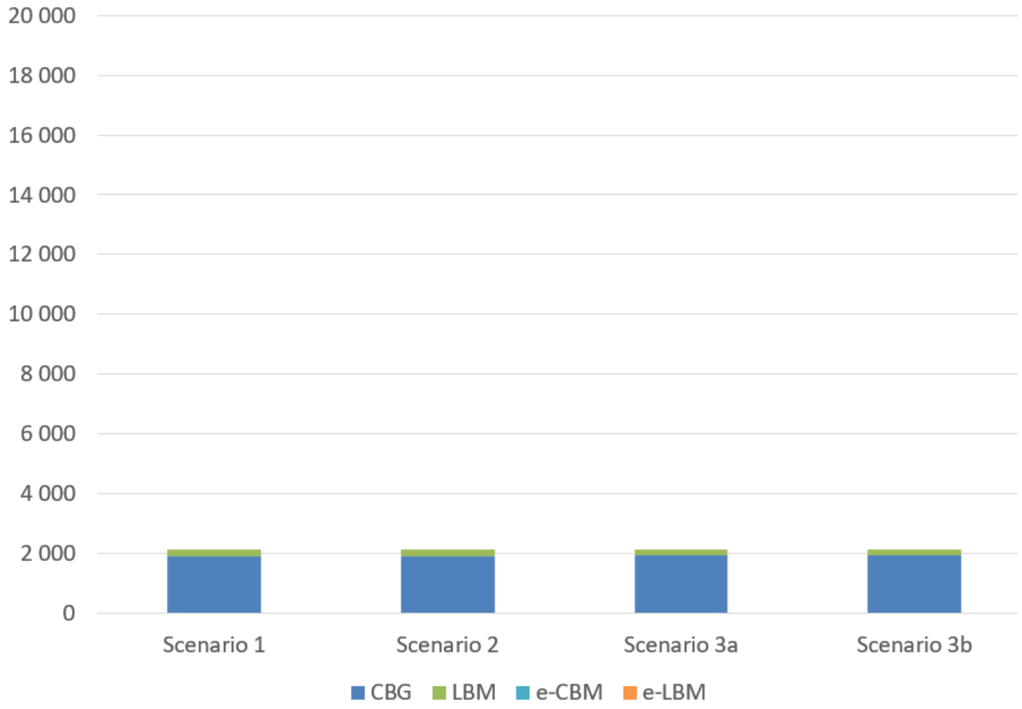

Figure 9. Production capacity for LBM and CBM. Dark blue colour indicates CBG production and green colour indicates LBM production. There is no e-CBM or e-LBM production capacity in 2021-

2030

Year 2030 has the production capacity increased for all scenarios but has also decreased for the CBM capacity and increased for LBM capacity. The transition from CBM to LBM happens because the demand has decreased for CBM and that producers therefore are assumed to have switched from producing CBM to LBM.

The production capacity is approximately 1 500 GWh for CBM for all scenarios and approximately 1 500-3 900 GWh for LBM for the scenarios where scenario 1 is the lowest and scenario 3b is the highest. The production capacity for the electrochemical routes is still moderate and corresponds to 50-160 GWh.

The increase in production capacity corresponds to a yearly increase in production capacity from the year 2021-2030 of:

- 90 GWh/year for scenario 1
- 160 GWh/year for scenario 2 including electrochemical pathways and 150 GWh/year excluding electrochemical pathways.

- 240 GWh/year for scenario 3a including electrochemical pathways and 230 GWh/year excluding electrochemical pathways.
- 370 GWh/year for scenario 3b including electrochemical pathways and 350 GWh/year excluding electrochemical pathways.

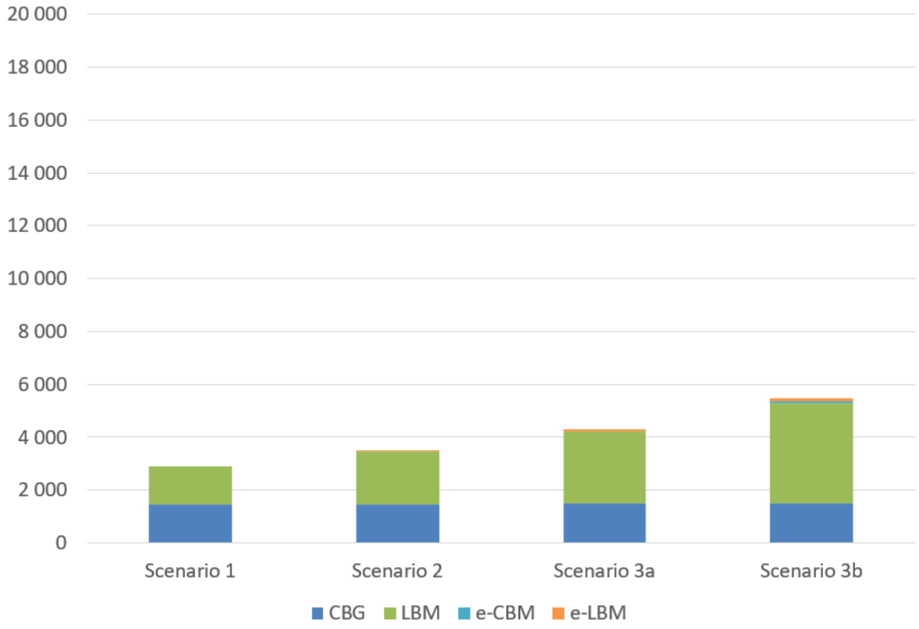

Figure 10. Production capacity for LBM and CBM. Dark blue colour indicates CBG production, green colour indicates LBM production, blue colour indicates e-CBM and orange colour indicates e-LBM production capacity.

2045

Year 2045 has the production capacity increased for all scenarios except scenario 1, the rest of the scenarios has also decreased production capacity for the CBM but instead also an increased LBM capacity. The transition from CBM to LBM is due to the fact that the demand has decreased for CBM and that producers therefore are assumed to have switched from producing CBM to LBM.

The production capacity is approximately 1 000 GWh for CBM for all scenarios and approximately 1 500-19 000 GWh for LBM for the scenarios where scenario 1 is the lowest and scenario 3b is the highest. The production capacity for the electrochemical routes is moderate for scenario 2 and corresponds to 300 GWh and higher for scenario 3a and 3b and corresponds to 6 900 respectively 7 500 GWh.

The increase in production capacity corresponds corresponding to a yearly increase in production capacity from the year 2031-2045 of:

- -50 GWh/year for scenario 1
- 200 GWh/year for scenario 2 including electrochemical pathways and 180 GWh/year excluding electrochemical pathways.
- 1 600 GWh/year for scenario 3a including electrochemical pathways and 900 GWh/year excluding electrochemical pathways.
- 1 600 GWh/year for scenario 3b including electrochemical pathways and 800 GWh/year excluding electrochemical pathways.

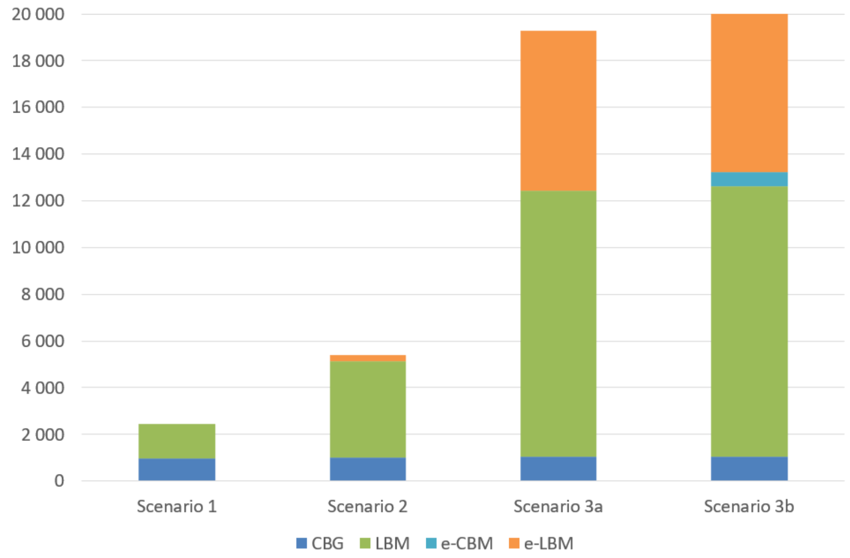

Figure 11. Production capacity for LBM and CBM. Dark blue colour indicates CBG production, green colour indicates LBM production, blue colour indicates e-CBM and orange colour indicates e-LBM production capacity.

5.3.2 Demand scenarios

The demand scenarios described in section 5.2 is shown below for year 2021, 2030 and 2045 respectively.

2021

Year 2021 is the starting value and corresponds to the existing demand in Sweden.

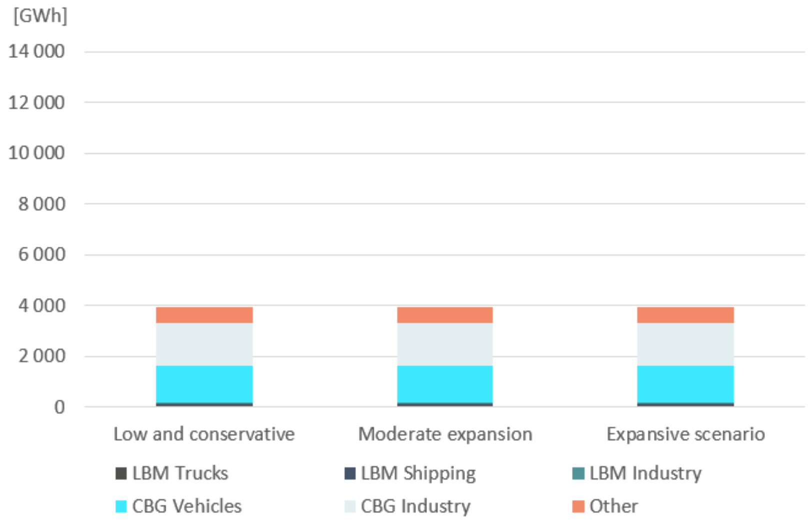

Figure 12. Demand scenarios for year 2021.

2030

Year 2030 has the demand increased for all scenarios but has also decreased from the CBG vehicles. The transition from CBM to LBM happens because the demand has decreased for CBM for vehicles and increased for the rest of the sectors.

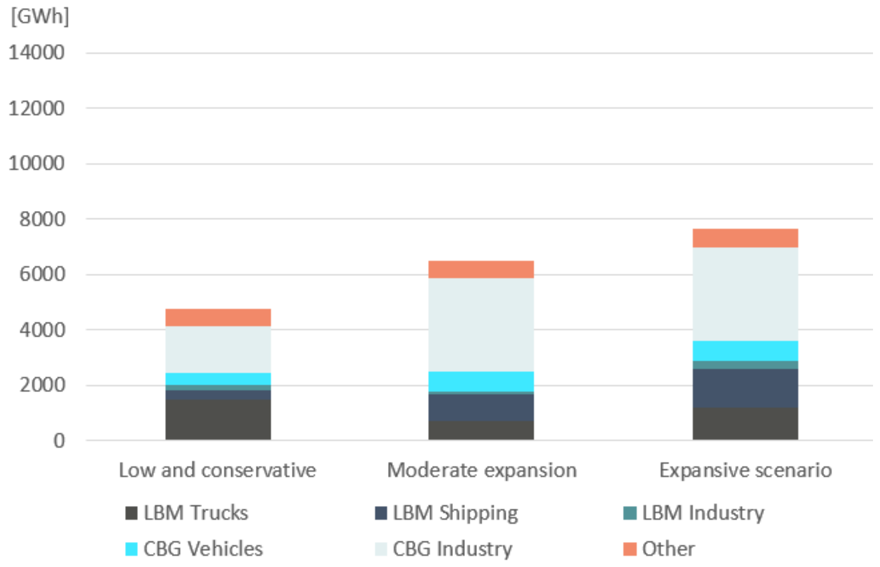

Figure 13. Demand scenarios for year 2030.

2045

Year 2045 has the production capacity increased for all scenarios except the low and moderate scenario, the rest of the scenarios has also decreased or nonexistent demand from the CBG vehicles. The demand for LBM for shipping, industry and heavy trucks is about 3.5 TWh per sector in the expansive scenario. The demand for CBM for the industry is also around 3.5 TWh.

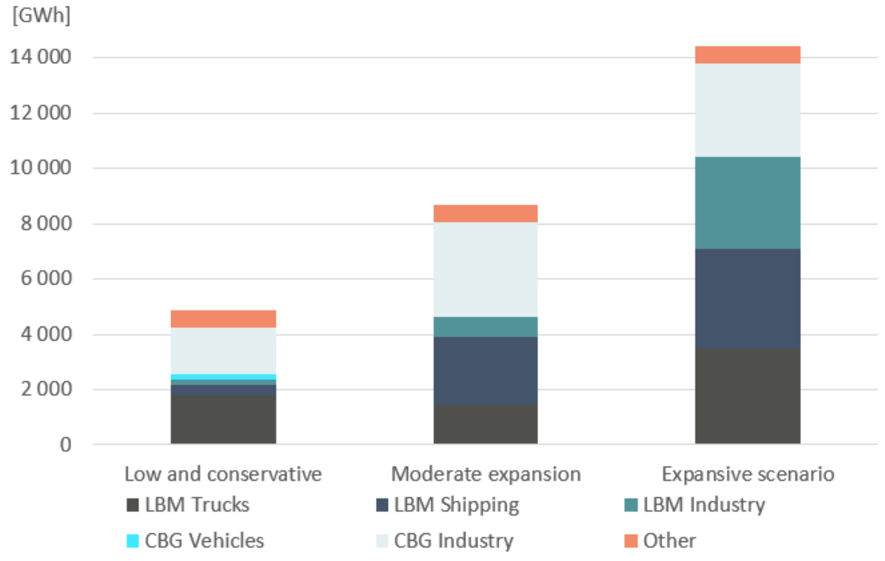

Figure 14. Demand scenarios for year 2045.

5.3.3 Scenarios - conclusion

Depending on the different levels of interest from society to support the production as well as the usage of LBM, very different future outcome can be expected in form of produced and consumed volumes.

The possible scenarios for production scenarios show that significant amounts of renewable bio- and electro methane can be produced and made available to the different sectors such as transportation and industry in form of compressed and liquified methane.

Analysing the demands in the different sectors shows also that similar amount of LBM can be consumed. All in all, an expansive production increase could be matched with demands and vice versa.

6 LIFE CYCLE ASSESSMENT AND CLIMATE PERFORMANCE FOR LBM

Assessing the environmental sustainability of fuels can be done with various different intents and purposes (Heinrich, 2010). Material requirements, energy requirements, and environmental emissions vary depending on the technologies used for LBM production and other fuel production processes. These aspects, in turn, affect the results of environmental assessments. Different materials have different environmental impacts, such as different levels of greenhouse gas emissions, and so-called "upstream emissions" from electricity used or metal mining vary between choices. The environmental impact from some of the LBM production pathways in this report is well-established, and others have not been fully assessed for the Swedish context before. This chapter investigates the environmental performance of the LBM pathways and tries to establish some general guidelines for consideration when using LBM in shipping. First, results when considering the European Renewable Energy Directive (RED II) are calculated. Then a life cycle assessment of some of the production pathways is presented to provide more insight to the environmental performance of LBM produced in Sweden in the future.

6.1 EU RENEWABLE ENERGY DIRECTIVE (RED II)

The EU directive RED II directs biofuels and renewable fuels in Europe and covers gaseous biomass fuels such as bio-methane (European Commission, 2018). It is a political document with the primary purpose of driving legislation to benefit fuel production from more sustainable biomass streams, i.e., biomass streams that do not compete with food crops or other alternative uses. It sets goals for reductions of climate impact compared to fossil fuels (set as a default of 94,1 g $CO_{2\text{-}eq.}$/MJ). For the future scenarios discussed in this report, savings of 65 % compared to the fossil default are mandated. In part, it includes annexes with default GHG values for steps in the biofuel production pathways: cultivation, process, transport, and distribution. Specific numbers for specific plant production are encouraged, but these default values can give a general overview of the GHG savings.

6.1.1 RED II calculations for LBM

GHG estimates of some LBM pathways were calculated using the default values in Annex VI of RED II (European Commission, 2018). The calculation for GHG emissions from production was therefore calculated using the following formula:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr},$$

Where:
E = total emissions from the production of the fuel before energy conversion;
e_{ec} = emissions from the extraction or cultivation of raw materials;
e_l = annualized emissions from carbon stock changes caused by land-use change;
e_p = emissions from processing;
e_{td} = emissions from transport and distribution;
e_u = emissions from the fuel in use;
e_{sca} = emission savings from soil carbon accumulation via improved agricultural management;

e_{ccs} = emission savings from CO_2 capture and geological storage; and
e_{ccr} = emission savings from CO_2 capture and replacement.

Emissions from the manufacture of machinery and equipment are not considered. For animal manure used as substrate, a bonus of 45 g CO_{2eq}/MJ manure (– 54 kg CO_{2eq}/t fresh matter) is added for improved agricultural and manure management. RED II dictates emission factors for electricity supplied from the grid at the regional grid average. The average value for Sweden today is approximately 14 g $CO_{2\ eq}$/MJ, including upstream emissions and trading. Electricity supplied via a direct connection to a power generating installation may use the emission factor of that installation. Wind power with 0 g $CO_{2\ eq}$/MJ power is assumed in the present work.

How e_{ccr} is to be treated in the case of carbon dioxide utilized from the biogas upgrade is not fully clear in the RED II directive, as this could be seen as an increased yield of the bio-methane plant and therefore to be considered as the same process. To not give unjust benefit to the electrofuel pathway, we consider e_{ccr} to be zero in the report calculations.

Thereby, the following terms are assumed to be zero in the present work:

e_l: waste material used as input in the biomass process.

e_{ccs}: no permanent CO_2 capture and storage

e_{ccr}: no fossil CO_2 is directly replaced

e_u: assumed to be zero for biogenic and electrofuels

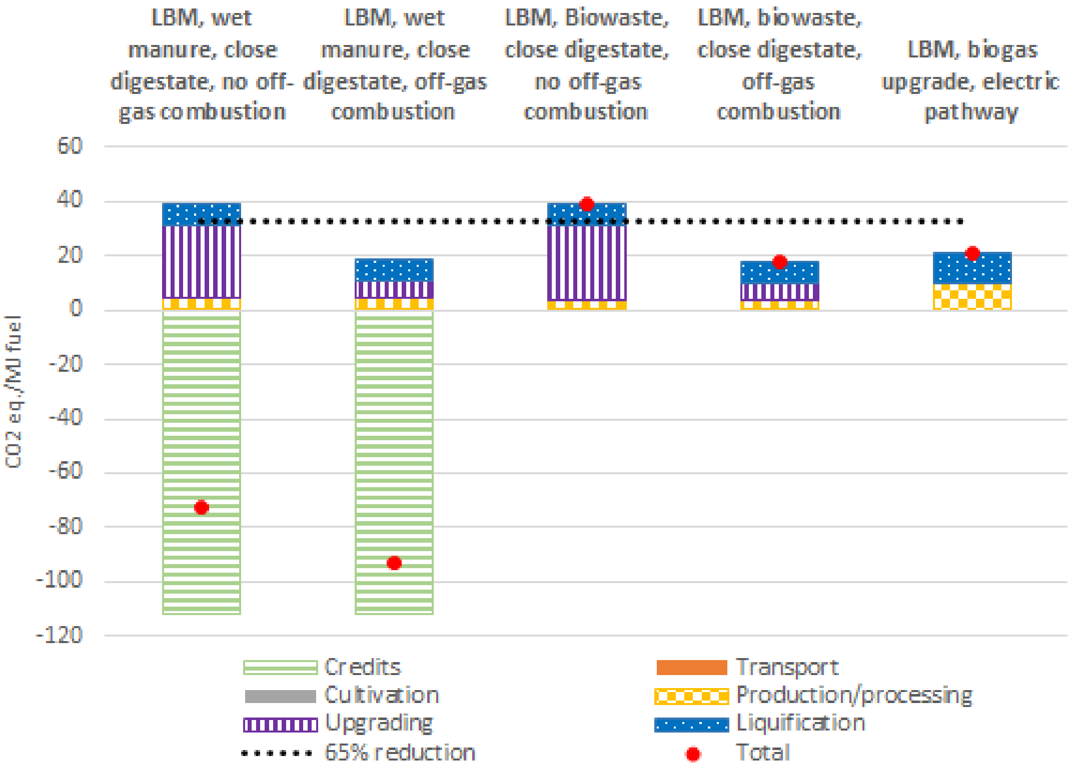

Figure 15. Calculations of three different LBM production pathways based on RED II, assuming Swedish electricity grid for support systems and fully renewable electricity as the main input for electric pathway.

The figure above shows the results from the calculations based on RED II. Note that the results from the GHG emission calculations do not include fuel use at sea, details on biowaste gathering, or capital goods. Most of the pathways meet the 65% reduction requirement (noted by the dashed line in the graph). These are default calculations based on the generic data presented in Annex IV, and there is a need to look into more detail on the actual emissions that can occur and the uncertainties around them throughout the value chain. In the following chapter, a more detailed analysis of the life cycle emissions of the electrofuel pathway is therefore presented as these are the technologies with the lowest technology readiness level. The analysis is presented together with a comparison to the biogenic LBM pathways.

6.2 LCA DATA INVENTORY AND MODEL ASSUMPTIONS

Fuel affects the surrounding environment when ships are used, and the human activities linked to producing the fuel and propulsion equipment have emissions. As RED II does not consider, for example, capital goods, some of the information on the performance of the fuels and potential future risks are not viewable when looking at these results. Instead, more complete life cycle assessments are required. A life cycle assessment (LCA) shows a technology or product's aggregated impact on a specific aspect of the environment, such as acidification or climate change. It indicates the primary emission sources and why they are there and makes it possible to benchmark different options.

Here LCA is used to assess the environmental impact and to identify trade-offs between options. The LCA is performed according to the ISO14044 standard (2006) and the recommendations for carbon capture and use related LCA studies from van der Assen et al. (2013) and Müller et al. (2020). Several value chains have been investigated to produce LBM, including a hybrid process where bio-methane and electromethane are produced in symbiosis. Five different fuels are compared: liquefied electro-methane, liquefied bio-methane from wet manure, liquefied bio-methane from gasification, LNG and MGO (as reference). Calculations were performed in the open-source tool OpenLCA. The LBM is used onboard a case study vessel traveling from Kiel, Germany, to Gothenburg, Sweden, based on data presented in Malmgren et al. (2021). The impact categories used are based on the International Reference Life Cycle Data System (ILCD) set of impact assessment methods (Heinrich, 2010) and include Acidification, Climate change (GWP20), Climate change (GWP100), Freshwater ecotoxicity, Human toxicity (cancer effects), Human toxicity (non-cancer effects), Marine eutrophication, Particulate matter, and Terrestrial eutrophication. Direct land use was also assessed.

Some of the biggest challenges in assessing the environmental performance of electrofuels are related to which processes that are included in the life cycle (Malmgren, 2021), e.g. if production of capital goods are included or not. In order to be able to assess the environmental impact of electrofuels, knowledge is needed about the future production path, use properties, emissions to the environment, and efficiency gains. The analysis here is primarily based on secondary data gathered through literature, as described in the introduction of this report. A flowchart describing the assessed fuel options is shown in Figure 16. The liquefied electro-methane is assumed to be produced with hydrogen from water electrolysis carbon from biogas upgrade, with a sensitivity analysis looking at carbon from direct air capture (DAC). The electricity is assumed to be wind power-based, and the methane is produced in a methanation reactor (Sabatier reaction). The methane is then liquefied to produce LEG, transported to the harbor. The system efficiency of electro-methane production varies between papers (Koytsoumpa et al., 2019; McKenna et al., 2018; Korberg et al., 2020; Monaco et al., 2018; Hoppe et al., 2018). Stenberg and Barlow (2016) is used as a reference for electro-methane production route (A in Figure 16). The biogenic LBM pathways are based on work by Börjesson et al. considering (1) waste or other biogenic materials transformed via anaerobic digestion to methane and (2) forest residue transformed via gasification (B and C in Figure 16). The LNG production is based on natural gas produced offshore in Norway (D in Figure 16), and MGO is based on European reference Life Cycle Database of the Joint Research Centers (ELCDs) global average (E in Figure 16) (ELCD, 2009). MGO propulsion is assumed to be performed using a medium-speed engine.

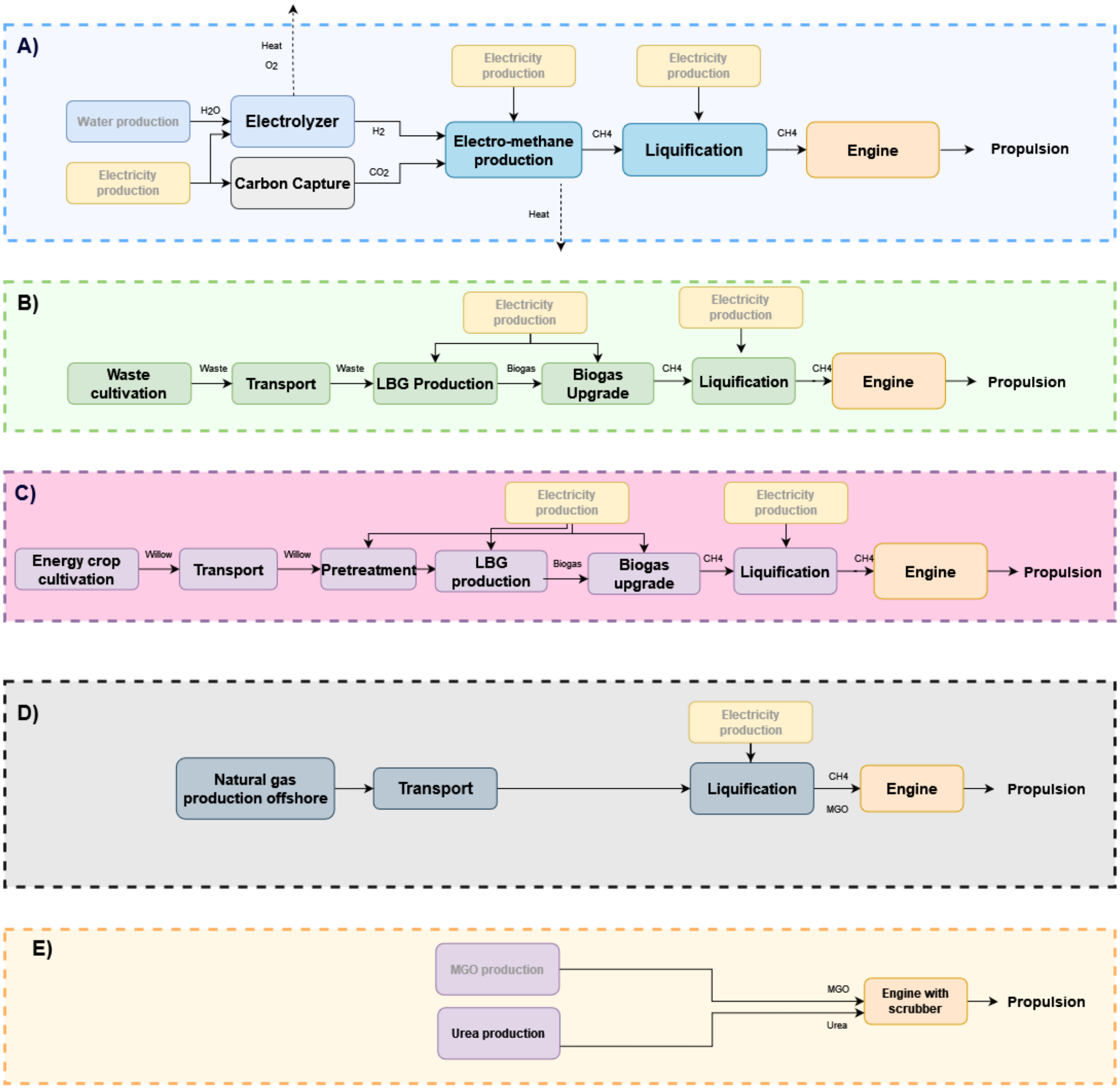

Figure 16. Generic outline for the five base scenarios assessed. A) Electrofuel production pathway of liquefied bio-methane, carbon capture technology not specified in the graphic. B) Bio-methane production pathway for LBM based on wet manure as input. C) Bio-methane produced through gasification of energy crops (not considered LBM in this report). D) Liquified methane produced from natural gas (LNG). E). Marine gas oil is used together with a scrubber to meet the sulphur emission requirements.

6.3 RESULTS

The first results in the second LCA study show that electromethane can be a relevant alternative to LNG in shipping if renewable electricity is used to produce the electromethane. Through the work in the project, it has been shown how access to renewable electricity is a requirement for electrofuels to contribute to a lower climate impact, and a reduction may only require electricity mixtures at levels with those in Europe today. The performance appears to be similar to biogenic options if renewable energy is used; however, in this system setup, no credits have been given to the source of the biogenic manure used to produce bio-methane. If this were included, the impact on climate from the biogenic waste scenario would drop significantly. As discussed in the previous chapter, this could also be the case if the electrofuel production pathway uses carbon dioxide from biogas upgrade and is viewed to share the source of the material.

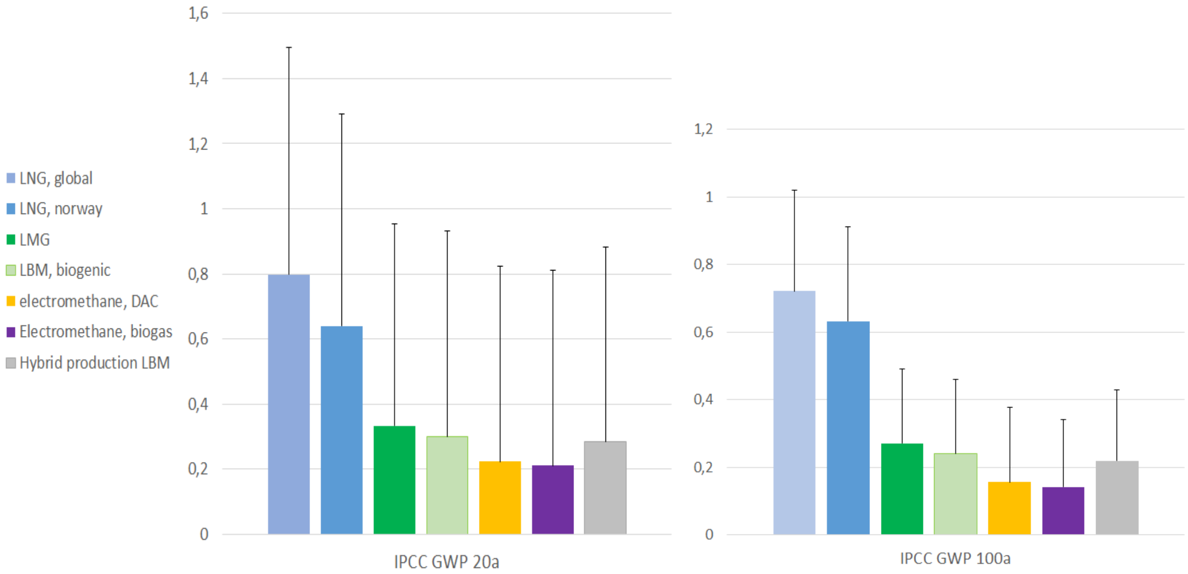

Figure 17. Climate change impact of different production pathways for liquified methane when used onboard a shipping vessel, normalized for a trip using marine gas oil (MGO = 1) Calculations based on the full fuel life cycle. Swedish electric mix used for electricity need for support systems, wind power with life cycle GHG emissions of 8 g CO_2 eq./MJ assumed for hydrogen production in electromethane pathways. No credits used for manure nor carbon displacement. A change in methane slip from the marine engines from 0.2g/kWh to 5.5g/kWh is indicated by the uncertainty bar.

Most investigated impact categories show no significant difference in the results when comparing LNG and different LBM pathways. There are some potential differences if the scope of the study is expanded, such as from capital goods investments. However, currently, the differences in results for acidification, eutrophication, and particulate matter are firm within the range of uncertainty for the study. Main influencing factors for the environmental performance overall besides electricity source include the sustainability of the coal source, marine engine properties, raw material extraction, and energy requirements for support systems in fuel production. LBM can potentially lead to reduced land requirements compared to if, for example, there will be a need for using gasification to provide methane for the European shipping fleet, thereby creating a need for land to cultivate crops on. Since the issue of land use is an essential factor in the biofuel discussion, this should be investigated further.

Large-scale expansion of LBM production in Sweden will lead to infrastructure development and new plant requirements. The current scope does not evaluate this in detail, and significant expansion might drive demand for materials and strain supply chains. A potential trade-off was identified between LNG and liquid electromethane: The use of electromethane may lead to an increased impact on toxicity in nature and humans due to higher electricity requirements. The same results are found in Malmgren et al. (2021) and Stenberg and Barlow (2016), but work is underway to identify the magnitude of this impact. The relevant emissions contained in a classic LCA of fuels are limited, and this result needs to be further investigated.

In the life cycle assessment results of liquified electromethane, the emissions from the biogas upgrading are included. This could instead be allocated to the bio-methane, as this is a necessary process to provide the product, leading to higher impact from bio-methane and lower from electromethane. The climate impact results for electromethane are up until the use phase similar to that of the RED II-based calculations. However, the use phase has a significant impact on the overall reduction from using fuel (RED II shows comparative reductions to fossil fuel without including combustion). As the use case presented here is specific to the shipping sector, the climate impact over the full life cycle varies if the methane is used in a different sector. The potential end uses are discussed and described in chapter 3 of this report.

7 COST BENEFIT OF SWITCHING TO BIOFUELS, INCLUDING SOCIO-ECONOMIC PERSPECTIVE

From a strict environmental perspective and especially seen from a greenhouse gas point of view, a switch within the shipping sector from using the fossil LNG to a renewable produced LBM is a very positive move. This is, at present, however not an easy move to take for a ship-owner due to the present economic cost structure in neither the globalised shipping sector nor within the domestic shipping sector.

A cost benefit analysis for present status will differ significantly with the situation to come including future measures on the policy side being presented and discussed in Chapter 4 and to some extent already decided. The upcoming changes will affect the economic calculations as well as other relevant perspectives.

Examples of parameters that will affect the total cost for running the vessels on either LNG or LBM are the cost for the fuel including possible future taxes and production incentives etc, costs connected with the emitting of GHG and other pollutants and/or costs for emission trading allowances that is suspected to be implemented.

Comparing non internalised costs for LNG and LBM used in shipping could be simplified just comparing greenhouse gases produced and emitted in a life cycle perspective as analysed in chapter 6. Reason for such an approach would be that the use phase of the renewable LBM and the fossil LNG would create the same environmental external effects in form of pollutants, noise, etc. There are however also other important benefits with the replacement of LNG with LBM such as making the society less dependent on imported fuels, the benefits of mineral fertilisers that can be replaced by the bio-fertilisers produced during the LBM production process etc. In below calculation example, only the carbon dioxide emissions have been accounted for via the costs connected with such emissions when shipping will be implemented in the EU emission trading scheme EU ETS.

A calculation example with a general cost for LBM production based on costs presented in Börjesson (2016) gives an approximate cost for LBM around 0.8-0.9 SEK/kWh. This cost includes production, liquification and distribution. This can be compared to the LBM production cost estimates for 2030 in Korberg et al. (2021) of 86, 91 and 142 Euro/MWh of liquid bio-methane, bio-electromethane and electromethane respectively.

A comparison with the LNG price will vary with the market price of that product which varies significantly over time. As an example, between 2017 and 2018, the LNG price as a marine fuel varied between 15 and 35 EUR/MWh, but since mid-2021 the bunker price has gone sky high and reached over 100 EUR/MWh. Traditionally, LNG has been cheaper per energy unit than traditional marine fuels such as MGO and HFO but for the moment LNG costs are double the costs for MGO/HFO which makes LNG not cost competitive. Assuming that this is an exceptional development, and that LNG cost continues to be available at a cost level of 30 EUR/MWh this can be approximated with the LNG fuel price of 0.3 SEK/kWh.

The price span between LNG assumed at a cost of 0.3 SEK/kWh and LBM at an approximate cost of 0.85 SEK/kWh that need to be bridged would in such case be some 0.55 SEK/kWh for liquid bio-methane.

With a proposed Swedish production support such as the biogas market investigation, the price of biogas for shipping could fall by about 0.40 SEK per kWh.

The emission trading cost within the EU ETS system of future assumed 100 EUR/ton CO_2 and an assumed reduction level of 65 % could generate an avoided emission trading cost of 0.2 SEK/kWh.

All in all, the future cost level difference between LNG and LBM seems possible to be closed or at least taken down to a level easier to finance from a ship-owner’s perspective. See Figure 18.

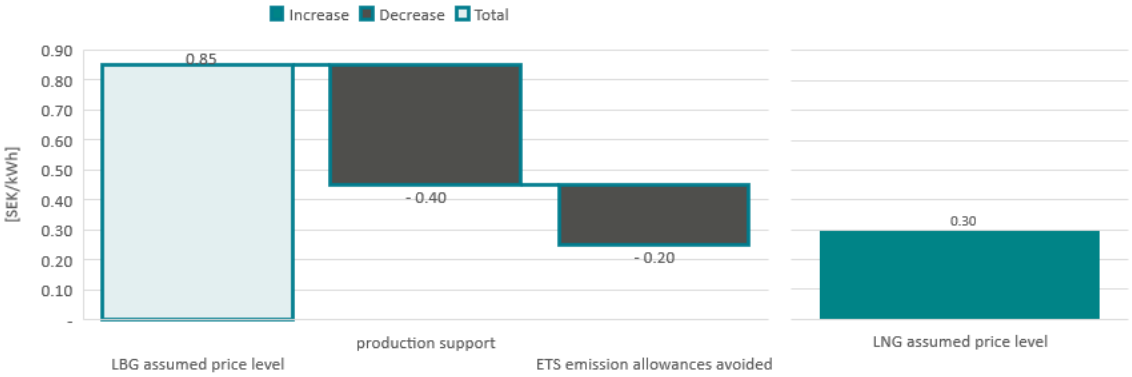

Figure 18. Calculation example with an assumed price level of 0.85 SEK/kWh compared to a similar assumed price level of 0.3 SEK/kWh for LNG also taking production support and ETS allowances cost into consideration.

8 DISCUSSION AND CONCLUSIONS

There are many different attempts to estimate the future role of LNG as a maritime fuel and according to DNVs latest regular energy outlook, it is predicted, in relation to future demands for fuels, that “Natural gas – mostly LNG – will take a 39 % share” by 2050 (DNV, 2021a). Also, zero-carbon fuels like ammonia, hydrogen, and other electro-based fuels such as e-methanol are predicted to be present but not at that high level as LNG. Other LNG predictions are more moderate such as the ABS Low carbon Shipping Outlook, which predicts about 10% LNG usage in shipping from 2030 and onwards. It is, at the time being very difficult to foresee and predict the outcome of a future that not only rely on technical and cost development but also highly on the development of policy instruments such as levies, taxes, regulations and other incentives. However, in this study, a future level of energy consumption in vessels of 15 % has been used for the estimates of total volumes to see if they potentially could be replaced with LBM. More as a starting point to see if a total energy share within shipping, being everything but insignificant, could be replace with LBM produced locally.

As reference values for the biogas production potential from Swedish substrates for anaerobic digestion in this study a maximum of 14 and 19 TWh/year for 2030 and 2050 respectively have been chosen. These values are based on the result from the most recent national biogas potential study, Börjesson (2021). Börjesson (2021) gives intervals for increased supply potential of different biomasses until 2050, where potential from manure & organic residues, straw respectively biomass from ecological focus areas & unused arable land have been considered being available for biogas production. In the category of ecological focus areas & unused arable salix is included. As salix is not suitable for methane production with anaerobic digestion not the whole of the estimated potential from this category would be available for biogas production. However, we have here assumed that part of sources from the category of sly, as part of biomass from field edges, overgrown pastures, pipelines, etc., that have not been included in the biogas production potential, will be suitable for anaerobic digestion and therefore might compensate for the salix. The values of 14 and 19 TWh/year does not include the biogas production that already exist, meaning that according to Börjesson (2021) a maximum of about 16 and 21 TWh/year for 2030 and 2050 respectively are possible scenarios. Restrictions regarding technical, economical and sustainability aspects have been taken account for in the estimations to make a scenario of a maximum, but nevertheless realistic, production potential. However, a strongly favourable development during the coming years regarding political incentives, policies and regulations related to energy, climate and agriculture on a national as well as a European level are a prerequisite for the realization of the whole calculated potential.

The production capacity of bio-methane could be **increased by electrochemical pathways combined with carbon dioxide from the upgrading of biogas**. There is also one advantage for the gasification route as there are already a methanation reactor present if the gasified biomass is to be used to produce methane because there is according to Held (2018) also an excess of carbon dioxide in the syngas available after the methanation of syngas. What is needed is then addition of hydrogen that can be produced via electrolysis of water. But electrolysers are costly and requires a significant amount of electricity which results in increased cost for combined bio-methane production (Korberg et al., 2021).

The result of the compilation in section *2.2 Compilation of existing and planned biogas production capacity* shows a clear market development were previously dominating CBG production will be replaced by a domination of LBM production as the mayor outcome from the biogas plants in the next few years. That’s because **demand for bio-methane is changing** and right now there is a transition from using CBM for road transport to using it as LBM in heavy road transport, industry and shipping. However, road traffic is moving towards electrification where it seems that heavy trucks are still favored but that they will also in the long run probably be replaced by electromobility.

The **policies and instruments proposed in Sweden** and the EU makes the future of Swedish bio-methane look relatively bright. A production subsidy for biogas will come, which benefits Swedish produced biogas and shipping because imported biogas has a production subsidy, and that shipping is tax-exempt. Industry also benefits because EU-ETS industries now have to credit biogas in their trading system, which they did not receive before.

The **production capacity of bio-methane could reach around 20 TWh by 2045 based on the techno-economic potential that exists**, but it requires that the profitability of the biogas sector is improved and that the challenge of time-consuming permits is improved, which means long-term stable conditions are required in order so that the industry should dare to invest. The reader should be aware that in order to reach the biogas market investigation's target of 10 TWh bio-methane in 2030, requires an expansion rate of 1 TWh / year by 2030, which is a major challenge.

The demand for bio-methane is quite difficult to predict until 2045, but it is largely due to technological development where **we can state that shipping and industry probably needs bio-methane if it is to be able to switch to renewable operation and production**. Electromobility can probably handle road transport and imported biogas can probably also handle some of the demand. However, the demand for bio-methane can also increase in Europe, which can mean that Swedish bio-methane can be exported because profitability is better abroad. Here it is required that the EU is harmonized around the bio-methane issue so that the bio-methane is used in the areas where it belongs.

In conclusion, it can be said that if renewable electricity is secured and sustainable biomass sources are used for the production of LBM, the climate impact potential from LBM is low. **Results from LCA calculations show that not only LBM originating from digestion shows good climate potential performance but also the production and use of electromethane produced from carbon dioxide from biogas upgrades seems to have good climate impact profile**.

As methane is a strong greenhouse gas even small leakage of methane in the life cycle could potentially change this conclusion (Bengtsson et al., 2011; Brynolf et al., 2014). The methane leakage in the engine has a significant effect on LCA results, corresponding to approximately 10-30% of the total GWP100 impact depending on engine technology and fuel production path.

For all methane-based propulsion alternatives, there is a risk of increased greenhouse gas emissions due to leakage of methane in the supply chain. In Sweden, on the other hand, there are regulations and voluntary commitments aimed at reducing methane emissions in the supply chain (production and distribution of biomethane).

This report shows that it could be possible to replace fossil LNG as a fuel in shipping with renewable LBM at a large scale from a Swedish perspective. The total bunkering of ships in Sweden are around 25 TWh per year, varies over time, and is dependant not only on which ships that calls Swedish ports but also with market competition with ports in other countries. Should be that 15% of that fuel be LNG, it would be some 4 TWh LNG that could be interesting to switch towards LBM.

The potential shift in Sweden from LNG to LBM at a level of 4-6 TWh is assessed to be a realistic potential, but the shift will not happen unless the society gives the industry incentives that supports that shift and clearly shows the involved stakeholders that there is a long-term strategy to enhance renewable methane production and consumption. It especially important that policy instrument in the shipping sector is introduced that connects greenhouse gas emissions with a cost that can be avoided if fuels with low or zero emissions being used.

Today, only a small proportion of bio-methane is liquefied to LBM in Sweden, while most of the planned production facilities for biogas will be for LBM, thanks to subsidies in the form of investment support and the decreased demand of CBG that benefits LBM.

A calculation example with a general cost for LBM production based on costs presented in Börjesson (2016) gives an approximate cost for LBM around 0.8-0.9 SEK/kWh. This cost includes production, liquification and distribution. This can be compared to the LBM production cost estimates for 2030 in Korberg et al. (2021) of 86, 91 and 142 Euro/MWh of liquid bio-methane, bio-electromethane and electromethane respectively.

The production support suggested in within the Biogas market investigation (SOU 2019:63), that was included in the Swedish governmental budget decided in late 2021, has not yet been formulated in detail. The suggested support according to SOU 2019:63 was however structured in three parts:

- A fertilizer gas premium of 0.4 SEK/kWh biogas produced from manure.
- A biogas upgrade premium of 0.2–0.3 SEK/kWh for biogas that is upgraded.
- A liquefaction premium of 0.1–0.15 SEK/kWh.

A Swedish production support at a level of 0.25-0.4 SEK/kWh and an emission trading cost of future assumed 100 EUR/ton CO_2 and an assumed reduction level of 65 % could generate an equally large, avoided cost of 0.2 SEK/kWh. These two measures will together have the possibility to decrease cost level for LBM down from 0.8-0.9 SEK/kWh to 0.3-0.4 SEK/kWh which would more or less even out the cost difference between LNG and LBM as a marine fuel. Over time, it is foreseen in this study that a larger part of the produced LBM will consist of bio-electromethane and electromethane estimated to come with a higher production price.

All in all, the future cost level difference between LNG and LBM seems possible to be close to zero or at least a lot smaller barrier to overcome. There are still many uncertainties such as future price differences, future levels of ETS, which reduction ratio for which LBM can benefit within the EU emission trading system, the future cost of ETS trading allowances etc. However, with a political will and a likely policy development, it seems at least possible that shipping companies with a will to reduce GHG emission through the switch from LNG to LBM would be able to solve that in relation to fuel economy. A future LBM fuel that has a larger share of e-methane will potentially also be more expensive. However, that is still difficult to determine and alternatives available and allowed at that time might also be more expensive.

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