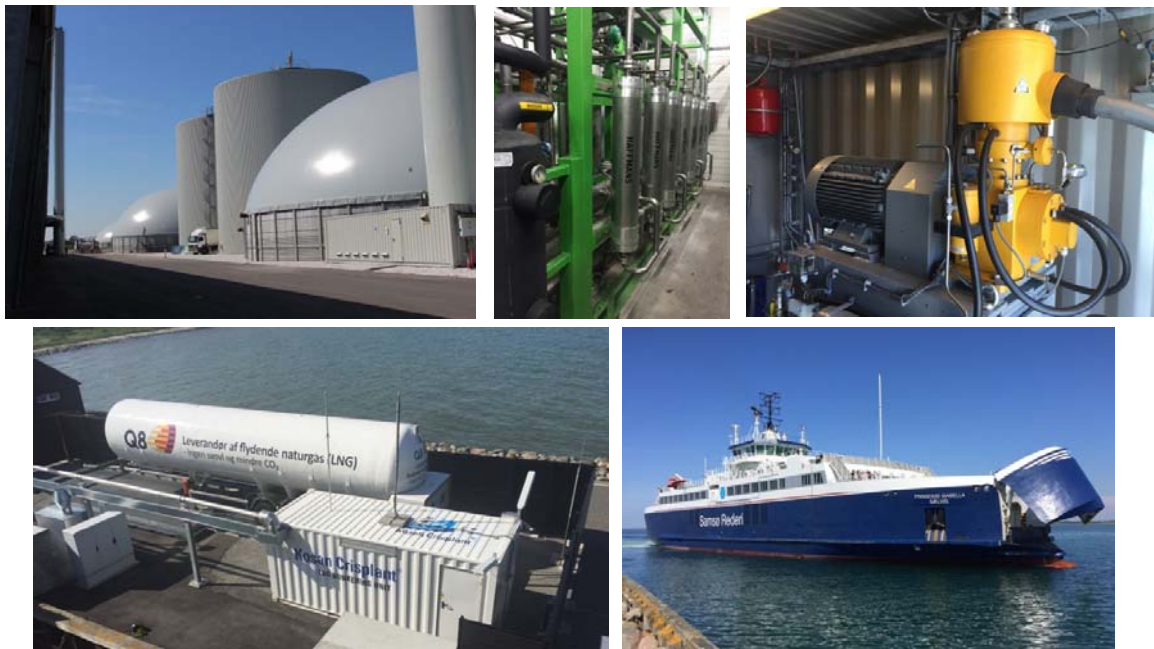


# Biogas Liquefaction and use of Liquid Biomethane

*Status on the market and technologies available for LNG/LBG/LBM  
of relevance for biogas actors in 2017.*



Biogas liquefaction value chain from waste to marine fuel

BioGas2020

**Interreg**   
Öresund-Kattegat-Skagerrak  
European Regional Development Fund

 **GoLNG**

 **Interreg**   
Baltic Sea Region  
**Go LNG**

### Colofon.

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## Table of content

Glossary and conversions .....	4
English Abstract .....	6
Norsk sammendrag.....	6
Dansk Sammendrag .....	6
Svenskt sammandrag.....	7
Introduction.....	8
Environmental aspects of marine transport .....	8
Energy consumption .....	9
Biofuel impacts .....	10
SO <sub>x</sub> , NO <sub>x</sub> and methane emissions .....	10
Brief historical LNG market trends .....	12
Methane liquefaction technologies .....	13
The scale of Liquefaction .....	13
Large scale liquefaction technologies.....	13
The present LBM production globally.....	14
Five steps towards LBM .....	15
Existing nano-scale liquefaction technologies.....	16
Economic aspects .....	21
The global LNG market .....	21
Market for deployment of LBM .....	22
Economical considerations for bio-methane liquefaction .....	22
Cost structure .....	22
Revenue streams .....	23
Scenarios for future marine fuel consumption .....	24
Market development for biogas for transport .....	25
Trucks.....	25
Buses.....	26
Trains .....	26
Social acceptability .....	26
Discussion for decision makers .....	28
References .....	29

## Glossary and conversions

The nature of combining different markets is that the terminology and conversions may not be familiar to all. A dictionary and conversion tables are needed

### Glossary

LBM	Liquid Bio Methane
LBG	Liquid Biogas
TPD	Tons Pr. Day
LNG	Liquid Natural Gas
CNG	Compressed Natural Gas
CBG	Compressed Bio Gas
GHG	Green House Gas
MTPA	Million ton pr. year
FSRU	Floating Storage Regasification Unit
ECA	Emission Control Area
MMBtu	Million British Thermal Units (used in U.S.)
LCA	Life Cycle Assesment
boe	Barrel of Oil Equivalent
loe	Liter of Oil Equivalent

Volumetric conversion tables

#### Methane CH<sub>4</sub> At 0 °C 1013,25 Hp

Nm <sup>3</sup>	ltr. Liquid	kg
1	1,695	0,717
0,59	1	0,423
1,395	2,366	1

	Ton LNG	m <sup>3</sup> LNG	M <sup>3</sup> gas	MMBtu	boe	loe
Ton LNG	1	2,22	1,3	53,38	9,20	1.467
m <sup>3</sup> LNG	0,45	1	585	24,02	4,14	658
m <sup>3</sup> gas	0,77	0,002	1	0,04	0,01	1,13
MMBtu	0,02	0,04	24,36	1	0,17	27
boe	0,11	0,24	141,3	5,8	1	159
loe	17,3	38	22.465	922	159	1

Gas Data:	SI Unit	65 % CH <sub>4</sub> (Std. biogas)	LNG G20 100% CH <sub>4</sub>	LNG 'Fossil' gas*	CH <sub>4</sub>	CO <sub>2</sub>
<b>Methane</b>	CH <sub>4</sub> vol.%	65	99,9	88,97	100	0
<b>CO<sub>2</sub></b>	CO <sub>2</sub> vol.%	35	0	0,99	0	100
<b>Density</b>	kg/Nm <sup>3</sup>	1,16	0,72	0,83	0,72	1,98
<b>High Heating Value [H<sub>hv</sub>]</b>	MJ/Nm <sup>3</sup>	26	40	44	40	0
<b>Lower Heating Value [H<sub>lv</sub>]</b>	MJ/Nm <sup>3</sup>	23	36	40	36	0
<b>High Heating Value [H<sub>hv</sub>]</b>	kWh/Nm <sup>3</sup>	7	11	12	11	0
<b>Lower Heating Value [H<sub>lv</sub>]</b>	kWh/Nm <sup>3</sup>	6	10	11	10	0
<b>H<sub>2</sub>S</b>	ppm (vol.%)	100	0	**2,7	0	0
<b>CO<sub>2</sub> emission</b>	kg/GJ			57,01		

\* Source: Energinet.dk gas quality for 2016

\*\* mg/Nm<sup>3</sup>

Density

CH <sub>4</sub> (LNG), kg/m <sup>3</sup>
CH <sub>4</sub> (20°C,1013 mbar), kg/m <sup>3</sup>
ρLNG/ρ0°C,1013mbar (-)

## English Abstract

This report is a brief introduction to the emerging field of cooperation between biogas producers and users of Liquid Biomethane. Environmental concern and regulations are the basis behind the emerging market with Green House Gas emissions and sulphur and NOx emission from Shipping.

Liquid Natural Gas market is processing and marketing natural gas at large scale on the global market, whereas the Liquid Biomethane markets is by nature comparatively on very small scale and often a local market, challenging the technologies and the economy of scale. However, the European market – giving stimulations for biofuel blending from 2021 according to a new Transport Energy directive under negotiations – is expected to grow fast.

Several companies have prototypes and few biomethane liquefaction plants are running, and this report gives an overview of the technologies and some of the basic environmental, technical, economical and social aspects that must be considered for implementing the sustainable value chain for Liquefied Biomethane. The report has focus on marine transport, such as ferries, but LBM can also be used for heavy duty trucks and trains.

## Norsk sammendrag

Rapporten er en kort introduksjon til et voksende marked for samarbeid mellom biogassprodusenter og brukere av flytende biometan. Miljø- og klimamessige utfordringer og reguleringer (klimagassutslipp og utslipp av SOx og NOx fra maritim transport) ligger til grunn for denne nye forretningsmuligheten.

Flytende naturgass fremstilles og selges i stor skala på et voksende marked. Derimot er flytende biometan av grunnleggende årsaker av en langt mer småskala og lokal produksjon til sammenligning, noe som utfordrer den tekniske og økonomiske lønnsomheten av små anlegg. I et forslag til nytt EU direktiv om energi til transport kan maritim transport få innblandingsincitamenter fra og med 2021, noe som vil øke verdien av flytende biometan signifikant i et større marked.

En rekke selskap har prototyper eller enkelte anlegg for flytegjøring av biometan er i drift, og denne rapporten gir en oversikt over teknologiene og noen av de miljømessige, tekniske, økonomiske og sosiale aspektene som må tas hensyn til for å realisere en bærekraftig verdikjede for flytende biometan. Rapporten har hatt fokus på maritim transport, eksempelvis ferger, men flytende biometan kan også benyttes i tungtransport og på tog.

## Dansk Sammendrag

Rapporten er en kort introduktion til et gryende marked for samarbejde mellem biogasproducenter og forbrugere af flydende biometan. Miljø- og klimamæssige udfordringer og reguleringer (klimagasudslip og emissioner af SOx og NOx fra marin trafik) ligger til grund for denne nye forretningsmulighed.

Flydende naturgas fremstilles og sælges i stor skala på et voksende verdensmarked. Derimod er flydende biometan af grundlæggende årsager af en langt mere småskalig og lokal natur i sammenligning, hvilket udfordrer den tekniske og økonomiske rentabilitet af små anlæg. I et forslag til nyt EU direktiv om energi til transport kan marin transport få iblandingsincitamenter for biobrændstoffer og dette vil kunne øge værdien af flydende biogas signifikant i et langt større marked.

En række virksomheder har prototyper eller enkelte anlæg i drift til småskalig forflydning af biogas og denne rapport giver et kort overblik over disse og de forhold af miljømæssig, teknisk, økonomisk og social

art, der skal analyseres for at realisere en bæredygtig værdikæde fra biogas til flydende biometan til fx skibstrafik – eller til tunge lastbiler og tog.

## Svenskt sammandrag

Rapporten är en kort introduktion till en växande marknad för flytande biometan (flytande uppgraderad biogas) med samarbete mellan biogasproducenter och förbrukare. Utmaningar inom miljö och klimat samt regleringar (utsläpp av växthusgaser, SOx och NOx från t.ex. sjöfart) ligger till grund för denna affärsmöjlighet.

Flytande naturgas (LNG) produceras och säljs i stor skala på en växande världsmarknad. Flytande biometan är av flera skäl en jämförelsevis mycket mer småskalig och lokal produktion, vilket ger en utmaning beträffande teknik och lönsamhet för dessa små anläggningar. I ett förslag till nytt EU direktiv om energi till transporter ser det ut som om sjöfarten stimuleras till inblandning av biobränslen och detta skulle kunna ge ett ökat värde på flytande biometan på en mycket större marknad.

En rad verksamheter har prototyper eller enstaka småskaliga anläggningar i drift med förvätskning av uppgraderad biogas (biometan). Denna rapport ger en kort överblick över detta med hänsyn till miljömässiga, tekniska, ekonomiska och sociala faktorer som skall analyseras för att få en bärkraftig värdekedja för biogas till flytande biometan. Rapporten har fokus på sjöfart som t.ex. färjor men flytande biometan kan också användas för tunga lastbilar och tåg.

## Introduction

This report takes a snapshot of the market situation for liquefied biogas for 2017. Many projects and consortia are working on LNG solutions and a few of these actors also consider the Liquefaction of Biomethane and it is expected to expand in the years to come. According to the draft version of the Renewable Energy Directive 2020 of the EU, the maritime sector will be met by demands of utilizing a proportion of biofuels, in order to reduce the GHG emission.

Liquefaction of methane (LNG) mostly takes place as liquefied natural (fossil) gas to increase the energy density, and make transport more flexible. Natural gas is primarily transported in low to medium pressure pipelines, and to some extent as compressed natural gas (CNG) for vehicles. Increasingly however, LNG is used to open new gas-markets, transported by ship or road trucker, and re-gasified before use. This new flexibility has influenced the world market prices significantly and on energy basis the LNG production is expected to reach 10% of the global crude natural gas production by 2020.

### **INFOBox 1.**

Compared to most hydrocarbon-based fuels, LNG has higher energy content, of about 45 to 50 MJ per kg higher heating value (HHV). Compared to compressed natural gas (CNG), LNG has an energy density greater by factor 2.5, which reaches approx. 22 MJ/litre. At atmospheric pressure, LNG occupies a volume 600 times less than conventional natural gas (Nguyen et al. 2017). Liquefied Biomethane (LBM) has approximately the same characteristics as LNG.

However, as the fossil gas reserves in e.g. the North Sea are diminishing and the global agreements to reduce the GHG emission from e.g. the transport sector, biogas is significantly increasing in importance. For instance, the present expansion in biogas production in Denmark is expected by 2030 (including methanation of CO<sub>2</sub>) to reach the expected (reduced) level of consumption of fossil gas by 2030, and to fully replace the fossil gas by 2050 (Nielsen, 2017).

As biogas is replacing some of the fossil gas market the process from biogas to liquefied Biomethane (LBM) will be described here. It is indeed technology under development, so this will not be a comprehensive overview, but will shed light on the most common technologies. The sources for the study are both a workshop held at Samsø, Denmark, in June 2017, where 4 companies presented their solutions and published reports/press releases of new innovations on the market.

A major challenge for the liquefaction process for LBM – compared to LNG – is the scale, as biogas rarely is produced in large quantities, so the technical challenge is downscaling. This will always be a challenge when liquefaction is done from a single biogas plant as we see the first cases of (see part xxx)

However, another option can also be pursued where there is a natural Gas Grid. Upgraded biomethane is injected in the national gas grid and from there a blend of biomethane and fossil methane can be liquefied and sold (partly) as liquefied biomethane, if accompanied by the appropriate Green Gas Certificates. In this case, a larger Liquefaction plant can be established and possibly another scale of economy is possible (Olsen, 2017). Two projects are trying to establish this type of liquefaction plant in Northern Jutland, Denmark (Rousing, 2017).

## Environmental aspects of marine transport

The fundamental background of this work is based on environmental aspects: The dwindling fossil energy resources, and the resulting challenges of Green House Gas emissions and climate changes. All sectors



depending on fossil fuels are looking into to increasing the energy efficiency and sustainable alternatives. So far the aviation and marine transport have not undergone the same restrictions and demands as land transport, but apparently this is changing.

Potential renewable energy sources for shipping applications include wind (e.g. soft sails, fixed wings, rotors, kites and conventional wind turbines), solar photovoltaics, biofuels, wave energy and the use of super capacitors charged with renewables. The transition to a clean energy shipping sector requires a significant shift from fossil fuel-powered transport to energy-efficient designs and renewable energy technologies, starting today. The shipping sector is now working serious to fulfil their 'fair share' of global GHG emission reductions as agreed upon in Paris 2016 (Figure 1).

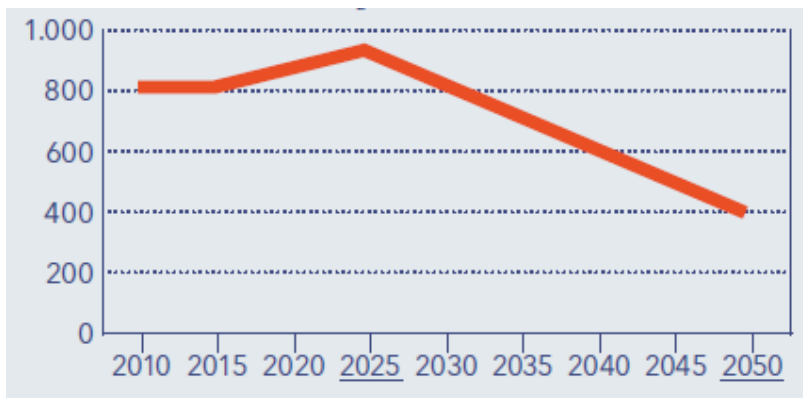


Figure 1, CO<sub>2</sub> emission (in Mio t Annually) with an expected increase due to global growth until 2025 and a proposed emission reduction of 50% by 2050 (Danske Rederier, n.d.).

The International Maritime Organisation under United Nations (IMO) have launched a strategy, not only to comply with sulphur and NO<sub>x</sub> emissions ceilings, but also to comply adequately to the goals set in the Paris Agreements, where shipping will reduce CO<sub>2</sub> emissions (European Commission, 2017b). For this to be effective, the sector has to look more into the biofuel alternatives, and the draft of EU Renewable Energy Directive (Article 25) (European Commission, 2017a) propose an incentive for blending of biofuels for the marine sector within EU from 2021.

### Energy consumption

In 2012, international shipping was estimated to have contributed about 2.2% to the global emissions of carbon dioxide (CO<sub>2</sub>). Although international shipping is the most energy efficient mode of mass transport and only a modest contributor to overall CO<sub>2</sub> emissions, a global approach to further improve its energy efficiency and effective emission control is needed, as sea transport will continue growing at pace with world trade (source [www.imo.org](http://www.imo.org) ).

In 2011 the IMO agreed upon the first binding CO<sub>2</sub> emission regulations, with focus on improving the energy efficiency by 30% in 2025. But with increase in world trade, energy efficiency is not enough to contribute to the global climate goals, and other energy sources should be identified and applied. The industry points at hydrogen, power and biofuels in a mixture with fossil energy in the future.

When considering environmental aspects from the fuel sector, the most prominent factor is usually the GHG emission as well as SO<sub>x</sub> and NO<sub>x</sub> emissions (see below). However, when considering LNG, the SO<sub>x</sub> and NO<sub>x</sub> emissions are already very low. Considering the role of biofuels, such as LBM, in shipping's decarbonisation, it raises the question of the shipping industry's involvement and awareness in the debates

bioenergy availability, utilization, and wider impacts (e.g. issues associated with land-use and life cycle emissions).

### **Biofuel impacts**

This indeed links shipping fuel to land-use, and the questions on the impact on land use of biofuels (Indirect Land Use Change –ILUC). The feedstock for the biofuels should not be energy crops, rather crop wastes, manure, sewage sludge and (industrial) food waste. Only in this manner we can avoid the ILUC and have a sustainable biofuel that can ‘fit into’ the agriculture and food industry. We call this 2nd Generation or advanced biofuels that has a strong GHG abatement profile. For land transport, this can be calculated to have a negative emission profile, when the biogas production is manure based (Nielsen, 2017).

However, producing methane can have one major potential drawback to consider. Methane has GHG values 20-28 times higher than CO<sub>2</sub>, and direct emissions from the production or the liquefaction is problematic, and should be taken care of in the normal operational procedures. It is better to flare methane losses, than to emit methane to the atmosphere, but where biogas is produced based on waste, we have a positive balance, if the biogas production plant has no loss of methane (Leakage in the individual production process). This also accounts for the following upgrading, liquefaction, transport, and bunkering of the methane (see the technical section).

Finally, depending on the vessel engine technology, a small proportion of methane may be emitted as unburned fuel (manufacturer of large ship engines state approximate methane loss of 0,2-0,5% with current technology) and this must also be eliminated in the strive towards sustainability.

### **SO<sub>x</sub>, NO<sub>x</sub> and methane emissions**

The agreed regulations in the Emission Control Areas (ECA) have already set the standard, the shipping industry is expected to follow the coming decades. This will reduce the emissions of SO<sub>x</sub> and NO<sub>x</sub> significantly. Dual Fuel LNG engines emits significantly less NO<sub>x</sub> and SO<sub>x</sub>. However, dual fuel engines may have a small methane slip (Schramm,2017) Apparently, single fuel methane engines can have a lower emission as compared to dual fuel engines, but no published information is available.

The GHG emission effect is very high in producing bio-methane, and therefore, the losses should be kept at an absolute minimum. This applies for all steps in the value chain. Generally, when the input is waste, manure or slurry for the biogas production, the overall Green House Gas emission reduction during production of biogas and use of methane is very high. Some reports even claim that through biogas for transport, you can actually achieve a net decrease in CO<sub>2</sub> emission – when considering intense meat production as societal necessity (Nielsen, 2017).

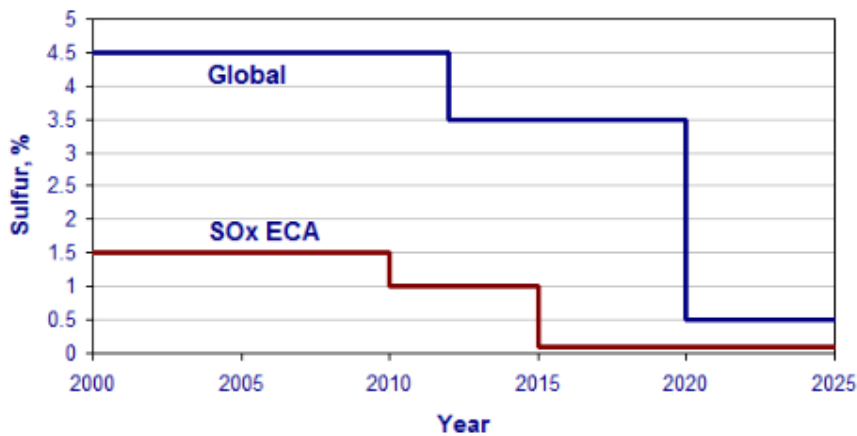


Figure 2. MARPOL sulphur limits (International Maritime Organization, n.d.)



Figure 3. Existing and proposed Emission Control Areas Source <http://www.cleanmarineenergy.com/mobile/shipping-emissions/>

Still, using mostly waste to produce the biomethane – whether compressed or liquefied – will have a significant GHG emission reduction effect. However, the compression and/or liquefaction requires 5-10% of the energy content of the ‘raw gas’, therefore the energy for processing should preferably be green power (PV, wind, or hydro-electric).

Transport and filling of vehicles present another challenge as LBM will boil off, if not constantly cooled, or maintaining a constant consumption from the fuelling tank. For instance, when filling a road truck tank, the vehicle should be kept on the road, fully utilizing the fuel in the tank (and not parked for the weekend) to reduce the risk of boil-off. This in praxis is more or less impossible, thus demanding each vehicle to have a re-liquefaction device installed.

Finally, the first generation of methane fuelled engines, had a significant methane loss, escaping thru the exhaust pipe, due to unignited gasses in the combustion chamber. This has indeed been the focus point of

the succeeding engine generations. The present (2017) state of the art engines, will not have a major loss from the combustion.

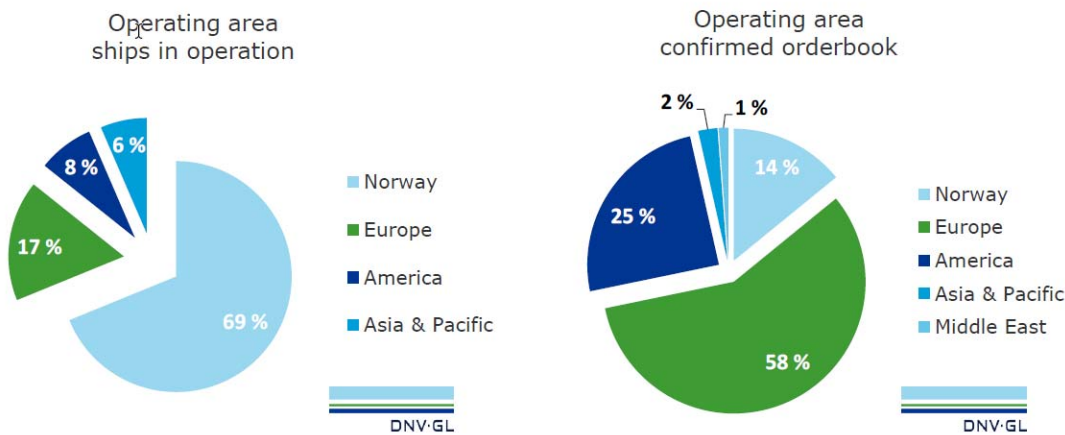
### Brief historical LNG market trends

In the present context, we can experience a strong development in the global LNG market, from a global production in 1990 of 50 million metric ton per annum (MTPA), which in 2016 had increased to 258 MTPA ((International Gas Union, 2017)), ie. a five-fold increase in 25 years. Global liquefaction capacity has added 35 MTPA of capacity between end-2015 and January 2017 to reach 339.7 MTPA.

The global LNG shipping fleet (to transport LNG around the world) consisted of 439 vessels as of January 2017, including conventional vessels and ships acting as floating storage units. In 2016, a total of 31 new builds were delivered from shipyards.

For the maritime industry, the Emission Control Areas demand low sulphur and from 2016 low NOx emissions from Vessels making the LNG fuel an interesting alternative, especially for ferries and local vessels operating in the Emission Control Areas (ECA). The demand for low emissions of SOx and NOx has paved the way for a change towards LNG in the local/regional shipping industry.

Ships carrying LNG as cargo have been fuelled by gas for over 50 years, but cheap fuels have been used for propulsion. The first merchant ship which was not an LNG carrier, but utilizing LNG as a fuel source, was the Norwegian ferry GLUTRA which was built in 2000. Since 2001, 77 LNG fuelled merchant ships have been built and are operating with about a further 86 ships under construction or undertaking conversion (Figure 4). Of the confirmed new builds and conversions, about 15 are in North America.



Updated 21 March 2016

Figure 4. 77 LNG fuelled vessels as of March 2016, and 86 confirmed newbuilds under way (2016-19). The expansion is seen in Europe and America, Norway leading the development (DNV-GL 2016)

According to DNV GL, the numbers will double every two years thereafter for the next ten years. If simply projected forward, to 2024, this gives 1 million tonnes in 2016 and 5.5 million tonnes in 2024, equivalent only to Hong Kong’s annual bunker sales volume and a fraction of the current global market for all bunkers, about 250 million tonnes a year (TRI-ZEN LNG market Perspective, 2014).

The use of LNG fuel for vessels is increasing, and although it is still only a very small fraction of global LNG consumption, the use of LNG for fuel in the shipping industry is increasing fast, due to ECA regulations.

## Methane liquefaction technologies

The choice of liquefaction processes has diversified during recent years, but basically it is the same overall technology to purify and cool down the methane for liquefaction. This report is, however, not a detailed technological comparison of the different technologies, but we merely try to describe the currently available solutions from a technical market specific point of view.

## The scale of Liquefaction

Liquefaction is usually done in large scale (> 1000 metric tonnes per day or 365.000 tonnes annually) at larger refineries, but when we are looking into biogas the process has to become downscaled, as biogas is usually not produced in large quantities.

We have to look into another scale of gas liquefaction as described by Cryonorm:

- Small-scale <500 Metric Tons LBM per Day or 182,500 tonnes annually
- Micro-scale <75 Metric Tons LBM per Day or 27,000 tonnes annually
- Nano-scale <10 Metric Tons LBM (or 13800 Nm<sup>3</sup> Biomethane) per Day (575 Nm<sup>3</sup> Biomethane /hour) or 3,650 tonnes LBM annually

The promotion of LNG as marine fuel, requires the development of small-scale gas liquefaction facilities at the biogas plants i.e. with a capacity (much) below 100.000 tonnes annually per unit and corresponding bunkering facilities in harbours, (Nguyen et al. 2017). The matching of the biogas production in nano-scale, requires either the match of a corresponding ferry to utilize the fuel, or perhaps future biomethane/natural gas blends to reduce CO<sub>2</sub> emissions of the Marine transport sector.

Presently two projects are being planned for in Denmark in the size of 150-300 tons pr. day using the existing gas grid with a blend of biomethane and natural gas for a blended liquefied methane (Rousing 2017, Olsen, 2017)

A recent study (Nguyen et al. 2017) mentioned a methane input of two tonnes/hour, which could be considered 'Micro-scale' production facility. However, in the project plan of Samsø Biogas, the annual estimated biomethane production is expected to be approx. 3,5 mio. Nm<sup>3</sup> of biomethane annually (approx. 30 GWh or 0.1 PJ), corresponding to 6-7 tonnes LBM per day (Samsø Kommune, 2017).

In this report, we choose to define the size of the facility as "Nano scale" and only few biogas plants globally are much larger than this size. The development of cost- and energy-efficient small-scale units is challenging, due to higher production cost per unit of LNG/LBM (no economy of scale effect), the profitability of the supply chain as such and design constraints.

## Large scale liquefaction technologies

LNG liquefaction can be grouped into two main categories (Roberts et al., 2015):

- Small to mid-scale LNG which relies on single pure refrigerants
- Large-scale LNG which relies on mixed refrigerants

For large-scale LNG, there are several variations of the mixed refrigerant (MR) technologies including:

- Propane pre-cool (C3MR), single mixed refrigerant,
- Dual mixed refrigerant (DMR),
- Parallel mixed refrigerant,
- Mixed Fluid Cascade Process (MFCP), and
- C3 MR with a nitrogen refrigeration cycle (AP-X) process.

More details on these technologies can be found <http://hub.globalccsinstitute.com/publications/ccs-learning-lng-sector-report-global-ccs-institute/38-lng-liquefaction> (Global CCS Institute, n.d.).

The most energy-efficient large scale liquefaction process is a cascade system (Andress, 1996) based on propane, ethylene and methane in three refrigeration cycles. It requires a high equipment inventory and is therefore not suitable for small-scale applications. Expander-based layouts build on different configurations of reverse Brayton cycles are compact, simple, and inherently safe since nitrogen is the most common refrigerant medium (Roberts et al., 2015).

However, they are generally less efficient than mixed-refrigerant processes [Nguyen et al. 2017], which operate with a mixture of hydrocarbons and nitrogen as working fluid. The refrigerant changes phase in the cryogenic heat exchangers, which presents the advantage of high heat transfer coefficients. The refrigerant composition may also be adjusted over time, if there are leaks of the most volatile components, or variations of the feed gas composition.

For large-scale Liquefaction of natural gas, a couple of companies seem to dominate the market:

- Air Products' liquefaction processes accounted for nearly 80% of existing plants in 2016, mainly the so-called
  - Nitrogen recycle LNG liquefier or single mixed refrigerant for below 250.000 tonnes annually,
  - Propane precooled mixed refrigerant process (above 250.000 ton annually)
- ConocoPhillips Optimized Cascade® process increasingly gathering market share for large plants
  - The Optimized Cascade process is based on three multi staged (Propane, Ethylene and Methane as refrigerants), cascading refrigerant circuits using pure refrigerants, brazed aluminium heat exchangers and insulated cold box modules.
- Mixed Fluid Cascade Process (MFCP) is a combination of cascade and mixed refrigerant technologies was developed by Statoil and Linde for the Snøhvit LNG Project in Hammerfest, Norway
- Shell's Dual Mixed Refrigerant is an evolution of the C3MR design, where the pure propane refrigeration circuits are replaced by a heavy MR circuit and spiral wound heat exchangers.

Other and increasingly smaller-scale processes make up a limited portion of existing liquefaction but this sector may see an increase in market share going forward. We will in the following explore this part of the market for micro-scale liquefaction (< 27,000 ton) and nano-scale (<3,650 ton annually).

## The present LBM production globally

Most of the existing LBM production (2017) worldwide is based on land-fill gas producing in total around 40,000 tonnes LBM annually (corresponding to 55 mio. Nm<sup>3</sup> of biomethane) (Table 1). For comparison, the largest Danish biogas plant produces around 21 mio. Nm<sup>3</sup> annually, so the global LBM production is still very limited. Bio-LNG/LBM production in 2016 (partly according to Groengas Nederland, 2016) and experiences gathered in this study is represented by the following (Table1).

Table 1. List of known existing biomethane production units.

Company/Technology	Country	Biomass source	Annual production of LBM (tonnes)
Hamworthy/Wärtsila Mixed refrigerant	Norway	waste	3,600
Hamworthy/Wärtsila Mixed refrigerant	Norway	waste	3,300
Air Liquide	Sweden	waste	4,900
Air Liquide	Italy	?	3,100
Gasrec, Mixed refrigerant	UK	landfill	6,000
Gasrec, Mixed refrigerant	UK	landfill	5,000
Linde, Single mixed refrigerant	US	landfill	7,200
Linde, Single mixed refrigerant	US	landfill	10,000
<b>Total LBM production</b>			<b>43,100</b>

The Norwegian Biokraft Skogn will inaugurate a new biogas plant with a Wärtsila LBM production facility in 2017, planning to reach 10.000 tonnes LBM annually in first phase and doubling that level in the future. Also, Cryo Pur (cryogenic upgrading and liquefaction) has started production from a plant in Greenville, Ireland, late 2017, based on agricultural waste, 1,100 tonnes LBM annually. In any case, the production of LBM is still at a very limited scale – and that is exactly the challenge. Biogas is produced in small quantities locally, and thus requires micro- to nano- scale liquefaction plants (typically < 10.000 tonnes LBM annually).

The niche for LBM is minimal in 2017, but is expected to increase, as the need for biofuels in transport sector will indeed increase due to UN climate agreements and EU directives. The advantages of introducing LBM in the marine sector are:

- 1) emission reduction of CO<sub>2</sub> from Marine sector and
- 2) all the well-known secondary benefits ('on land') of creating jobs by producing waste based energy and fertilizer for the local farming systems.

LBM can be transported relatively easily and it can be dispensed to either LNG vehicles (trains or heavy-duty trucks) or CNG vehicles (light duty trucks and buses)– thereby 'extending' the gas-pipe system, by 'connecting' more distant biogas plants to the grid – or 'extending' the gas grid to distant gas costumers (virtual pipeline), such as the shipping industry.

This requires a liquid-to-compressed natural gas refuelling station equipment which creates CNG/CBG from LNG/LBM feedstock. Liquid natural gas is transported at relatively low pressures (e.g. 1.5 – 10 bar), but because it is a cryogenic liquid (i.e., temperatures at -162 °C) it requires special handling. A significant disadvantage of LBM is that storage duration should be minimized to avoid the loss of fuel by evaporation through tank release valves, which can occur if the LBM heats up during storage. However, this can be avoided by new re-liquefaction technologies on the market.

### Five steps towards LBM

The process from biogas to LBM has several major steps that can be solved in an integrated upgrading/liquefaction or in separate steps combining different technologies followed by transport and bunkering facilities.

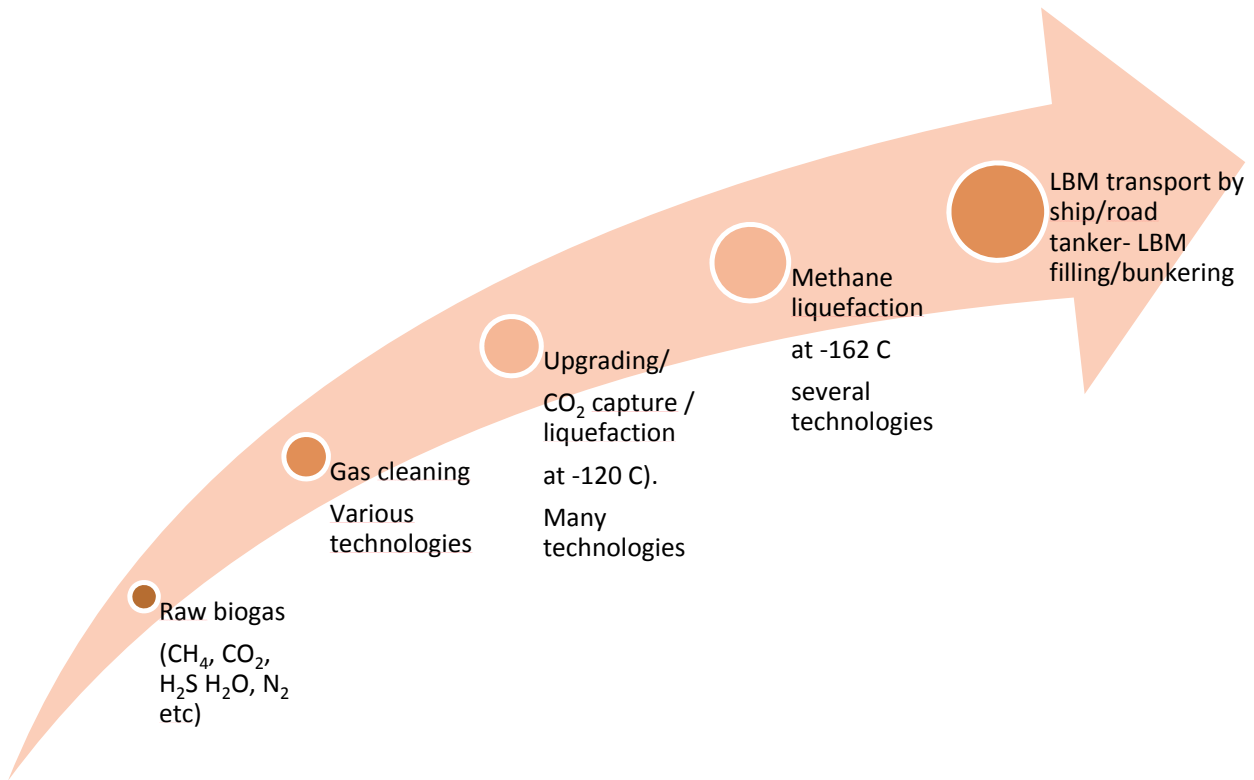


Figure 5. The major steps from biogas towards LBM. For further explanation, see text.

Depending on the following processes, the H<sub>2</sub>S removal from the raw biogas can be done by coal filters, biological scrubbers and precipitation by Iron Chloride. All are standard technologies at existing biogas plants (Alleque & Hinge 2012). The purity of the resulting gas depends on the gas use.

After step one, the ‘upgrading’ of the biogas to pure methane has been developed into numerous techniques, each with their advantage/disadvantages – and the technology selected is depending on the further use of the gas. The most common separation is by adsorption/absorption or membrane separation (see overview by Alleque & Hinge 2012), and in most cases the CO<sub>2</sub> is emitted to the atmosphere.

However, when using cryogenic separation, the CO<sub>2</sub> can be extracted as liquefied and a foodgrade marketable product. In addition, when seen in the context of a biogas plant, the need of energy for the processes and the use of excess heat are very important factors for the specific business case. See Table 2 for existing technologies on the market. The list is not complete, but includes what we have been able to find and have a dialogue with.

### Existing nano-scale liquefaction technologies

Based on a Samsø ‘Field to Ferry’ concept for liquefied biomethane (LBM) the companies below have given their potential solutions for this nano-scale gas treatment solution from raw biogas to LBM. The case expects to produce some 6 mio. Nm<sup>3</sup> of biogas (some 685 Nm<sup>3</sup>/hour) or 3,5 mio Nm<sup>3</sup> biomethane (400 Nm<sup>3</sup>/hour). The resulting LBM production would be around 2700 tons annually, fulfilling the energy need of the ferry Prinsesse Isabella.



Table 2. Existing technologies on the market (based on company info)

	Cryo Pur	Wärtsilä (Wärtsilä Puregas Solutions & Wärtsilä Gas Solutions)	Nærenergi Danmark A/S and Galileo SA	Air Liquide Advanced Technologies	Kosan Crisplant	Pentair Haffmans / Stirling Technologies	Biofrigas AB
<b>Technology used (short description for non technical personnel)</b>	Integrated upgrading and liquefaction system based on cryogenic upgrading (with Mixed Refrigerant Integrated Cascade). The impurities present in the biogas (water, H <sub>2</sub> S, VOCs, siloxanes, CO <sub>2</sub> ) are removed through anti-sublimation. Pure biomethane is then liquefied, and pure CO <sub>2</sub> is recovered in liquid form.	Upgrading: Amine upgrading and further dried in a pressure swing adsorption process. Liquefaction: Wärtsilä's MR (Mixed Refrigerant) process is based on a simple screw compressor and a proprietary mix of refrigerants. It is a fully closed loop solution.	Cryobox technology based on high pressure gascompressor. The gas is cooled under high pressure (250-300bar), and then condensed by reducing the pressure to the desired level (typically 2-3 bar). Uncondensated gas is recirculated and re-used. Cryobox can be delivered in 2 sizes and can be combined in parallel if the capacity is higher.	Biogas upgading: membrane filtration; CO <sub>2</sub> polishing: Pressure and swing adsorbtion; Liquefaction: reverse turbo brayton	Kosan Crisplant liqurefaction is based on the multi-refrigerant principle in a new more energy efficient process demonstrated in the micro-scale test Liquefaction Plant currently running. The multi-refrigerant principle is chosen due to its capacity possibilities and its energy efficiency. The scalable system makes it very easy for the customer to increase their supply as the demand rises.	Membrane separation + cryogenic separation CH <sub>4</sub> / CO <sub>2</sub> , stirling cooling generator	CryoSep is the unique system that upgrades and liquefies raw gas to BIO-LNG in the same plant. The technique used is cryogenic, cooling the raw gas in steps to -165C in these steps, the gas is purified to pure methane 99%.
<b>Production Capacity/range [day/year]</b>	Range of standard units to treat from 100 to 2000 Nm <sup>3</sup> /h raw biogas (1 to 22 tpd bio-LNG). Each unit can between 50% and 120% of the nominal biogas flow. For example, CF 600 unit: Min 300 - Max 720 Nm <sup>3</sup> /h raw gas = 3-7,3 tpd bio-LNG = 1000-2600 tpy bio-LNG	Upgrading: Standard capacities range from 200 to 6000 Nm <sup>3</sup> /h of raw biogas. Liquefaction: Standard capacities range from 6 to 25 ton/day of LBM.	Cryobox 600: 15,6 ton/day -or 5500-5700 ton/yr Cryobox 200 (Cryobox Bio): 4,8 ton/day - Ca. 1650-1800 ton/yr	from 5 metric ton per day) up to 50 TPD of liquefied methane	Build in modules of 17 tons/day or 50 tons/day. Production capacity day: 22 hours production Ton = 17 Vol m <sup>3</sup> = 40 Nm <sup>3</sup> consumption = 20.656 Production capacity year: 320 days production Ton = 5.440 Vol m <sup>3</sup> = 12.800 Nm <sup>3</sup> consumption = 6.609.964	+/- 5 t/day, 360 * 5 = 1800 t/year	CryoSep has a capacity of 500 to 1200 Nm <sup>3</sup> /day of Raw gas. Liquefaction of 300- 840 kg Bio-LNG per day
<b>Site requirements [m<sup>2</sup>] (footprint of facility)</b>	About 30 x 20 m footprint, to be housed under a ventilated or open shed.	Upgrading plant appr. 14 x 20 m. Liquefaction plant appr. 12 x 18 m. Above values includes access and maintenance space but excluding site roads.	2,646 m ( with) x 12,328 m ( lenght)	300m <sup>2</sup>	The Liquefaction plant is placed inside one 40 foot and an additional 20 foot container. Site requirements for storage tank will depend on size and placement (Horizontal/vertical).	L 20 m / W 10 m / H 5 m	40' Container need 12 m x 3m => ~80-100 m <sup>2</sup>

<b>(Range of) production cost pr. (kg./liter/ton/Nm<sup>3</sup>)</b>	Mainly electricity consumption: 0,6 to 0,7 kWh/Nm <sup>3</sup> of raw biogas (total for pretreatment-upgrading-liquefaction). More details available upon request.	Production cost depends mainly on electricity cost. Specific electricity consumption: - Biogas Upgrading 0,15 kWh/Nm <sup>3</sup> Raw Biogas - Biogas Liquefaction 0,70 kWh/kg LBG - Miscellaneous 0,10 kWh/kg LBG Heat consumption for biogas upgrading: 0,63kWh/Nm <sup>3</sup> Raw Biogas	O &M cost is primarily power consumption of 0,75 kWh pr. kg LBM. The resulting cost (no tax) of 0.70 DKK/kWh the cost of power is 0,525 DKK/kg LBM.	The CAPEX is depending on scope of supply. The electricity demand is - upgrading: ~ 0,25 kWh /Nm <sup>3</sup> of raw biogas - liquefaction: < 1 kWh/kg of LBG	We can build in modules of 17 tons/day or 50 tons/day. Estimated production cost: 0,7 kwh/Kg LNG, excluding pre-treatment of gas. Power consumption: 550 kwh	Range between € 0,30 - € 0,45 per kg of LNG, depending on energy (electrical) cost,	Production cost depends mainly on electricity cost. ~0,1 Euro/kg for upgrading and liquefaction.
<b>Operation and management costs</b>	Automated plant. Cryo Pur offers a full-service agreement including remote monitoring, replacement of spare parts, and availability guarantee.	Depends on labour cost and energy. The plant is designed for unmanned operation, however, typically about 15 minutes of supervision is required 3 days per week. Required maintenance is typically 14 man days per year of which many tasks can be done in parallel.	IN addition to power, other OPEX will be around 0,11 DKK/kg LBM	Maintenance cost are ~3% of CAPEX/year	– Gas cost: the cost of biogas as the main input) – Energy cost needed to power the liquefaction plant, – Maintenance and replacement cost: Est. annual cost for a 17 tons/day liquefaction plant: 417.000 DKK. – Personnel costs. – Other O&M costs: include administration costs, health and safety related expenditures and clothing for personnel.	Energy consumption +/- 1,2 kW per kg LNG (incl +/- 2 kg Liquid CO <sub>2</sub> ), operator +/- 20 hours week	Depends on labour cost and energy. We offering a full service agreement including remote monitoring and replacement of spare parts. Required maintenance is typically 7 man days per year.
<b>Methane slip (Boil Off, if none, please describe how boil off is recovered/ avoided)</b>	No methane slip: expected recovery rate is 100%, 99.5% guaranteed. (During upgrading, CO <sub>2</sub> is removed as a pure liquid, with no methane slip. The biomethane is liquefied at 15 bar, so to produce bio-LNG at a lower pressure, some of the liquid is flashed, and the boil-off is re-sent to the liquefaction).	Guaranteed maximum methane slip from biogas upgrading is 0,1 % CH <sub>4</sub> , however, the typical value is about 0,05 % CH <sub>4</sub> . No boil-off handling system is required. Production of LBM happens at a temperature cold enough to compensate for heat ingress in the storage tank.	Due to the closed cooling loop, the process lead to no boil-off gas. The non-condensated gas will be recirculated and kept into the closed circuit.	< 0,5% of incoming methane from biogas, can be reduced to zero emission if required. NO BOIL OFF: the LBG is cooled down to -163°C, in case the vapor phase in the tank increases, the liquefier will automatically adjust the temperature set point and subcool the LBG at temp < -163°C	The use of LBG from the liquefaction plant is both safe and secure. The associated risk of methane leaks are minimized and the unique 30-minute stop-and-go function of the liquefaction plant ensure that demand and supply are balanced at all times, thus mitigating the risk for boil-off from the tanks. Should BOG however occur the gas will then be re-directed to the Liquefaction process, enabling no methane slip in the process.	No methane slip, the separation of CH <sub>4</sub> and CO <sub>2</sub> by membranes & the cryogenic separation is 100%, the installation produces 100 % CO <sub>2</sub> (99.998 % pure) and a Bio LNG (>98% CH <sub>4</sub> ). In normal process no methane is lost to environment	Methane slip < 0,1%. The boil off is re-sent to the liquefaction.

<b>Advantages</b>	<ul style="list-style-type: none"> <li>- Integrated unit: <ul style="list-style-type: none"> <li>- No interface between upgrading and liquefaction.</li> <li>- Low power consumption (combined cryogenic upgrading and liquefaction).</li> </ul> </li> <li>- No methane slip</li> <li>- Only consumable = activated carbon</li> <li>- Heat recovery for heating the AD</li> <li>- Production of liquid CO<sub>2</sub> as a valuable by-product</li> <li>- Operation flexibility from 50% to 120% of the nominal flow rate</li> <li>- Automated operation</li> <li>- Availability and performance guarantees</li> </ul>	<ul style="list-style-type: none"> <li>- Low methane slip</li> <li>- Low power consumption</li> <li>- Robust and reliable technology that is simple to operate</li> <li>- Designed for unmanned operation</li> <li>- Easy start-up and shut-down</li> <li>- Compact and modularized design</li> <li>- Solution is based on standard components to offer a low</li> </ul>	<ol style="list-style-type: none"> <li>1. Simple transport and on-site mounting delivered in two parts to assemble.</li> <li>2. Simple plant with easy maintenance. The total process is run by one simple and stable compressor in the Cryobox, with a minimum of rotating parts to maintain.</li> <li>3. Cryobox is delivered for outdoor operation with no need for building - although is can be installed indoor.</li> <li>4. Short start time of 10-25 minutes from 'hot' condition</li> <li>5. Fully automatized process with distant surveillance</li> </ol>	<p>One solution from biogas to bio-LNG with one supplier. High ratio of CH<sub>4</sub> extracted from biogas and low methane slip. A proven reliability of 98% of available running time. A trouble free solution for liquefaction with unsurpassed life time. Waste heat recovery in hot water (85°C) used for digester warm up. O<sub>2</sub> partially removed from biogas. Simple and understandable process easy to operate and maintain. Flexible solution automatically adjusted to raw gas flow and composition. Compactness ensures delivery in remote areas and reduces footprint. Air Liquide industrial organisation for providing world class after sales services.</p>	<ul style="list-style-type: none"> <li>- Start-stop time of 30 minutes. The process can run when prices are low, and stop when prices are high.</li> <li>- Scalable liquefaction technology reduce initial investment with options for increments</li> <li>- The plant is principally fully automatic, but needs monitoring, administration, maintenance etc.</li> <li>- LNG as well as LBG: The possibility to produce LBG helps reduce emissions of harmful particles and the CO<sub>2</sub> content in the liquefied gas.</li> <li>- An efficient liquefaction technology leads to lower cost per unit of LBG produced.</li> <li>- Low initial investment cost. The plant can be delivered as a Turnkey plant or under a EPC contract.</li> <li>- Plant in containers will ensure a limited footprint.</li> <li>- Allows the use excess heat for district heating or biogas process.</li> </ul>	<p>robust , stand alone system, easy to understand and operate, no methane slip, low amount of operator involvement,</p>	<p>No need to transport sludge to Bio-LNG plant – the plant is onsite. Biogas produced is in liquefied form that meets vehicle use requirements of -165 C and 1 bar. Upgrading of the raw gas and liquefaction of methane occurs in the same facility and systems. The separated carbon dioxide is available in liquid phase. The residual product from the plant is heat that can be used in the digestive chamber.</p>
<b>Disadvantages</b>	<p>New technology (though already demonstrated and already commercial).</p>	<ul style="list-style-type: none"> <li>- Advanced technology requires skilled personnel (training and support can be given in Scandinavian language)</li> <li>- The MR fluid requires careful handling, but the refrigerant is contained within the process thanks to the fully closed loop</li> </ul>	<p>If there is a huge capacity corresponding to several cryo-boxes, a larger plant could be a cheaper solution.</p>	<p>Limited number of references. Technology only validated on a test plant.</p>	<p>high investment</p>	<p>New technology</p>	

<b>Number of facilities and production capacity installed world wide</b>	2 references for biogas upgrading and <u>biomethane</u> liquefaction: - 1x 120 Nm <sup>3</sup> /h unit on WWTP biogas in France 2015-2017. - 1x 340 Nm <sup>3</sup> /h unit on agricultural/household waste biogas in UK (Northern Ireland) Nov 2017.	Upgrading: 31 existing plants with capacities ranging from 200 - 5000 Nm <sup>3</sup> /h. Liquefaction: 1 existing plant and 2 under construction with MR technology. 3 existing small scale LNG plants with another liquefaction technology. The same technology is used for re-liquefaction on board ships of which we have 7 plants under construction.	70 LNG/LBM installations worldwide, which could treat biogas	>50 biogas upgrading units, 16 methane liquefaction plant 2 biogas to bio-LNG plants	Kosan Crisplant has built more than 3500 LPG cylinder filling plants, with a global organisation to support the business. Kosan Crisplant has only build their first LNG/LBG test liquefaction plant able to produce 1 ton/day. Bunker Holding, NGF Nature Energy and Kosan Crisplant aim to lunch the first LNG/LBG Liquefaction plant in Port of Frederikshavn, Denmark. The Plant will be a 150 tpd plant delivered by Kosan Crisplant.	Pentair Haffmans biogas upgrading + liquid CO <sub>2</sub> +/- 36 installations, Stirling cryogenic liquefaction units > 500 installations world wide,	# 1
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All these technologies have pros and cons, and the choice depends on many other aspects of the biogas plant (e.g. heat needs) and the market (incl. subsidies and bio-tickets) for LBM and CBG or raw biogas

## Economic aspects

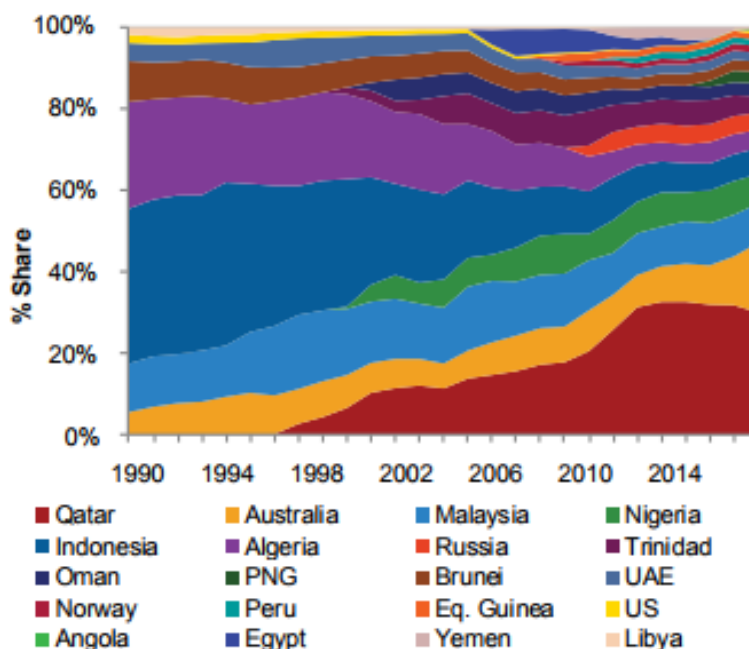
### The global LNG market

For the LBM market to develop the LNG market is the forerunner. For a new fuel “the chicken or the egg” paradox is always the challenge. In this LBM case, the LNG logistics and the world market is opening up for ships to use LBM in the future. LBM has advantages over LNG in terms of environmental /climatic performance, but disadvantages in terms of economy of scale and market development. Therefore, a brief intro to the growing LNG market in the following.

Qatar and Australia accounts for 47% of the export, followed by Malaysia, Nigeria, Indonesia, Algeria and Russia are the largest exporters (International Gas Union, 2017).

The largest importer is Japan (32%), followed by S. Korea, China and India. So, LNG market is mainly centred on Middle East and Asia. The largest global trade flow route continues to be Intra-Pacific trade. Continuing growth in Chinese and Indian demand, as well as Australian production, will cement this trade route’s prominence. Trade between the Middle East and Pacific was the second-highest by volume, due to Qatar’s role in supplying Japan and South Korea (International Gas Union, 2017).

In addition, the interest in LNG continues to grow for different reasons in various countries, such as decline in national gas production or to seek to reduce independence from e.g. Russian gas imports to Poland and Lithuania. Also, the Shale gas from US has now allowed the US to become exporter of LNG.



Source: IHS Markit, IGU

Figure 6. Share of global LNG exports by country 1990-2016 (International Gas Union, 2017)

There is significant variation in the LNG price among various geographic regions. Due to shale gas availability, North America has the lowest natural gas price, with natural gas (Henry Hub price) trading in a range from 2 to 4 USD/MMBtu (mio British Thermal Units) since 2012. However, the actual price of LNG delivered to a ship’s fuel tanks is a critical factor in the financial feasibility analysis and this cost is subject to some uncertainty based on the supply chain as well as the pricing model chosen by the supplier. (IMO feasibility study 2014, <http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/Third%20Greenhouse%20Gas%20Study/GHG3%20Executive%20Summary%20and%20Report.pdf> ).

Recently, the shipping industry has started to apply LNG as the main fuel for vessels. Boil-off of methane during transportation in the LNG transport vessels has been used for decades, and this has been the basis for developing new engines with high efficiency and low emissions at competitive prices in ECA zones with emission restrictions for shipping.

However, the world market is fed by large scale liquefaction plants and the above describe micro- and nano-scale liquefaction for biomethane feeds into another local market.

## Market for deployment of LBM

In 2017, the price of LNG is significant lower than the Marine Diesel (MDO) or Marine Gas Oil –the most relevant alternatives for dual fuel engines. The current price levels on different markets can be found here (<https://shipandbunker.com/prices#MGO>), but future prognoses of price development are difficult to find. However, with the increase in LNG market and the creation of new markets across continents, it can be foreseen that the gas prices are expected to remain lower than oil products.

LBM can readily replace any LNG installation, but so far this has only happened in a few cases as it is often difficult to compete with the low LNG price. The Air Liquide plant in Lidköping, Sweden, is selling a part of their LBM for trucks and buses in Norway (Charbagi, 2016) but it is difficult to find specific examples of vehicles or boats using LBM directly.

In 2016, a LBM fuelled ferry was demonstrated in Oslo and several ferries are ready in Norway to change to LBM at LNG market price, when the production increases. However, the low world market price for LNG is a great obstacle for the competitiveness of the LBM – without feed-in tariffs – or the future EU Renewable Energy for Transport directive demanding Biofuel application.

The heavy-duty vehicles fuelled by LBM/LNG are on the road in the US and Canada. Iveco and Scania will in 2017 deliver the latest version of LNG technology and Solbus do have a LNG/LBM bus since 2012.

The shipping industry is worldwide a huge consumer of fossil fuels and the shipping industry has increased since the fossil fuels were implemented in shipping. To get an idea of the order of magnitude, the energy consumption of Danish shipping totally in year 2000 was around 100 PJ annually. For comparison, Danish road transport consumed 93 PJ, national and international flights around 38 PJ in 2005. However, the national Danish shipping consumed only 5,6 PJ in 2015 when national biogas production was 6,3 PJ (Energistyrelsen 2016).

## Economical considerations for bio-methane liquefaction

Basically, when going to nano-scale, the project has to find every single integration benefit and look for a market for this, such as excess heat and the released CO<sub>2</sub>. Indeed, also the running cost on energy input is very crucial. In the following we present some initial considerations for decision makers.

### Cost structure

- Investment costs
  - where should the upgrading/liquefaction take place,
  - gas security issues,
  - heat recovery,
  - Sustainable power/energy supply (wind-power, straw for heating etc.)
  - innovative investment subsidies should be considered
- Biogas plant; Upgrading/liquefaction; Storage; Bunkering; LBG trucks.

- The liquefaction plant is still not a standard buy from the shelf,
- indeed, the companies have an interest in co-investment for demo-purposes as the market is so young and there are several competitors.
- Operation costs
  - The price of sustainable versus conventional energy
  - Staff/salaries;
  - Transport – leasing or buying;
  - Feedstock/consumables,

### Revenue streams

- LBM costumers.
  - In islands/very remote areas there might be only a single costumer which can make biogas value chain possible, but also vulnerable
- Feed in tariff. Feed in tariffs for biogas production can have significant influence
  - selling the value of 'Biotickets<sup>1</sup>' for the transportation sector
- Gate fees for waste treatment where biogas plants treat sewage or industrial wastes
- Selling fertilizer.
  - The digestate is a fertilizer product that can be refined into 'designer' fertilizers (e.g. fibers or liquid fertilizers)
- The option of (also) selling raw gas (for industry) or Compressed biomethane for CBG in transport sector should be considered

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<sup>1</sup> Comparable to the guarantees of origin for renewable energy, biotickets are in fact contracts between market parties regarding the purchase and sale of biofuel rights, and are not attached to the physical biofuel consignments. <https://cms.law/en/NLD/Publication/Dutch-implementation-of-the-Renewable-Energy-Directive-for-biofuels>

## Scenarios for future marine fuel consumption

When considering the choice of fuel for shipping other alternatives must be considered. Quite a few of the LNG ferries are gas-electric, where gas-engines produce power for the propellers. This means that they can/could readily become hybrid ferries introducing batteries to help for instance manoeuvring in the harbours. Especially when the power is from renewable sources makes this attractive.

A recent study (Wolsing 2016) has considered the fuel choice for new ferries. Electrical power is indeed the most efficient energy carrier with a total efficiency of 61%. Batteries are evolving fast, but still the storage capacity cannot allow to dream of larger and longer-sailing ferries to be fuelled solely by power from battery technology. The study showed that when there is less than 45 minutes sailing distance (depending on ferry size) batteries should be considered.

Hybrid installations are one way to address the problem of scaling, one example of this is Danish Scandlines. Scandlines have retrofitted their ferries sailing between Denmark and Germany. All four ferries have exchanged one of the diesel engines (1/5) and replaced it with a battery bank. Saving 65 tons in weight and an estimated fuel saving of 1,2 million liter diesel annually pr. ferry (Stensvold, 2014).

Consistent with the Paris Agreement, emissions will need to be reduced significantly and even reduced to zero during the second half of the 21st century. A recent study (Smith et al., 2016) shows that a number of energy efficiency interventions, alternative (low carbon) fuels such as biofuel and hydrogen can become preferable to the use of extremely low operational speeds in combination with fossil fuels in the marine sector. Future low-carbon-emission vessels may be fuelled by hydrogen, batteries and LBM for instance using fuel cells – and combinations hereof – depending on the technological development.

Purchasing ‘offset’ or biotickets can also be an option to reduce carbon footprint and the take up of biofuels in the marine sector varies among the scenarios, based on the assumption used on bioenergy availability. Scenario 10 has the largest take up of biofuels in accordance with the high bioenergy availability in this scenario. In this case biofuels reaches about 35% of the total fuel supply in 2050. The take up of biofuels is also significant in other scenarios (about 10 - 13%) of the total shipping energy demand in 2050. The gap between the price of biofuels and conventional marine fuels is not modelled in the report (they are set at the same price as their fossil fuel equivalents) because it is assumed that it will gradually decrease, therefore, the key parameter is their availability.

One consequences of this demonstrated potential significance role of biofuels in shipping’s decarbonisation is that it raises the necessity of shipping increasing its involvement and awareness in the debates around bioenergy’s availability, use and wider impacts (e.g. issues associated with land-use and life cycle emissions).

Scenario 7 (Smith et al., 2016), which involves the largest rate of take-up of LNG, demonstrates the consequence of lower capital costs and energy efficiency equipment). LNG gains a larger market share, because it is the machinery of choice from 2015 onwards (Figure 7).



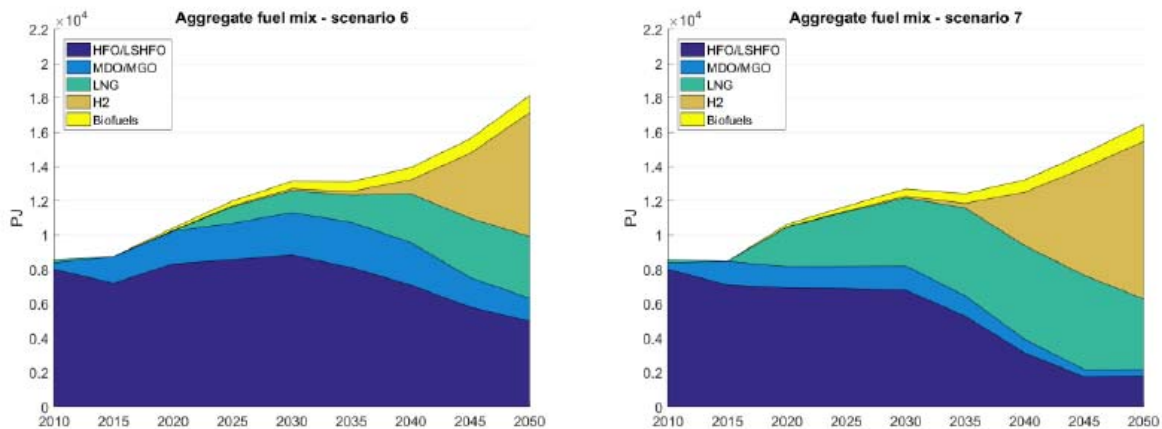


Figure 7. The aggregate fuel mix for two of many scenarios (Smith et al 2016)

## Market development for biogas for transport

The biogas sector accounts for 66,000 jobs in Europe, out of which most are in rural areas, generating ‘inclusive’ growth (including the local society in decisions and the job creation). In 2015 Europe had > 17.000 biogas plants and >350 biomethane upgrading installations and these numbers are increasing (<http://european-biogas.eu/biogas/>). Germany by far outnumbers other countries, but the development here is stagnant. However, many plants are developing, and increasingly biogas is understood as a potential engine for circular economy, and a necessity to be able to supply the transport sector with increasing demands for renewable fuels.

Upgrading and injection into the Gas grid is an option in many areas which – with biomethane certificates can make biogas available for transport in many regions. However, it is expected that the tendency towards liquefied natural gas for heavy vehicles and for shipping is going to drive the next step towards the phasing out of fossil fuels by conversion of biogas into biomethane and further on to Liquefied Biomethane (LBM), a very concentrated fuel comparable to fossil fuels.

## Trucks

Trucks fuelled by LNG/ LBM are clearly superior to CNG/CBG in terms of operation distances. Iveco has launched the newest engines with 400 hp and 1.700 Nm with CNG, LNG and Combi-solutions with operation distances between 570 and 1500 km (IVECO, 2016b). The only differences are the fuel tanks for LNG or CNG (Figure 8).



Figure 8: Operation distances for new trucks (IVECO, 2016).

Scania can deliver gas-fuelled engines of 280 or 340 hp (Scania Norge, 2016), fuelled by either CBG or LNG with 280 hp / 1.350 Nm or 340 hp/ 1.600 Nm for the P or G-series. Larger engines are under way and new versions such as Volvo Methane Diesel Euro VI, to be ready ultimo 2017 with 460 hp / 2300 Nm and 420 hp/ 2100 Nm (Franzen, 2016). Furthermore, it was mentioned during the debate of a biogas for transport seminar in Vestfold, Norway during May 2017 that Scania next year is going to present a 13 litre gas engine with around 500 hp and over 2.000 Nm (<https://www.biogas2020.se/nye-volvo-lastebiler-pa-biogass/>).

Still the market for LNG deployment is low – partly due to establishment of LNG filling stations. It can be expected to have a small jump due to the news release of the new Volvo methane diesel truck (Volvo Trucks, 2017). This truck is by far the best heavy-duty truck running on biogas on the market today, with up to 460 hp and 2.300 Nm it can compete on even the long hauls.

Litra AS, one of the largest transport companies in Norway with around 500 trucks has signed an intention accord with Skagerak Naturgass AS on buying 100 biogas trucks the next five years and in return Skagerak Naturgass AS will develop the fuelling infrastructure, first part in the Oslofjord region (Skagerak Naturgass AS, 2017). Air Liquide has entered the Norwegian market on biogas by taking over the majority ownership of Skagerak Naturgass AS (51%). The Norwegian dairy Tine will invest in 30 new trucks driven by LBM from the new LBM biogas plant in Skogn.

### Buses

Solbuss delivers CNG or LNG buses and LBM is already in use in Trondheim, Norway

### Trains

A recent feasibility study has shown that there are potentials for converting diesel trains to LBM in Norway, (Norsk Gassforum, 2015), already in use in the US and India. (<https://www.navigantresearch.com/blog/rail-looks-to-move-the-lng-market> )

## Social acceptability

In a sustainability analysis, the social aspects must be included – and it is not a straight-forward analysis as the value chain in LBM fuel analysis is by nature cross-sectorial. Many studies exist on the biogas production and the social acceptance of this way of producing biofuel in general and apart from some NIMBY-effects (Not In My Back Yard, see <https://peopleandbiogas.com/en/> ), it is generally accepted that waste-based (manure, crop wastes, food wastes etc.) biogas is among the most sustainable biofuels available, given the present amounts of waste from food and agricultural industry.

Corporate Social responsibility (CSR) is based on voluntarism to act responsibly and ahead of the international regulations. A study on CSR in Shipping (Arat, 2011) concludes that because customers now demand more than just the lowest prices for products they purchase, responsible business culture and CSR terms has spread from land based industries to shipping industry as well. Increasing trend shows that shipping industry already use CSR and acts responsibly, not just following international rules and regulations, but also voluntarily, acting responsibly on their own areas of business.

## Discussion for decision makers

One major challenge for increasing both the LBM production and the use of LBM in the shipping industry is that both sectors normally, do not have a common market – or a common terminology. Waste treatment and biogas production is a rather local phenomenon, only recently starting to focus on the transport market, whereas marine fuel purchase is a globalized market.

To make these ‘worlds’ meet, numerous things have to be taken into account and an adequate timing, too: Local ferry planning and local biogas planning and the idea of combining these two aspects. This has to be combined with interested private (and/or public) investors and a willingness to pay for the non-internalized values of green gas as compared to the low world market prices on fossil energy.

If the value chain from fields to marine vessels should grow in the future, the coming legislation should either

- require mandatory biofuel blend in marine and aviation sectors (creating a market due to environmental regulation and a business via biotickets) or
- adequate subsidies for this specialized, still expensive due to innovativeness and scale, but very promising combination in terms of climate gas reduction.

If the global heavy-duty transport (marine, trucks, trains, aviation) is to become low-emission in the future, the societal demand for finding the technical solutions will pave the way for research and innovation. But some market regulation has to follow, to make good show-cases of this promising concept.

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## Summary

This report is a brief introduction to the emerging field of cooperation between biogas producers and users of Liquid Biomethane (LBM). Environmental concern and regulations are the basis behind the emerging market with Green House Gas emissions and sulphur and NO<sub>x</sub> emission from shipping.

Liquid Natural Gas market is processing and marketing natural gas at large scale on the global market, whereas the Liquid Biomethane markets is by nature comparatively on very small scale and often a local market, challenging the technologies and the economy of scale. However, the European market – giving stimulations for biofuel blending from 2021 according to a new Transport Energy directive under negotiations – is expected to grow fast.

Several companies have prototypes and few biomethane liquefaction plants are running, and this report gives an overview of the technologies and some of the basic environmental, technical, economic and social aspects that must be considered for implementing the sustainable value chain for Liquefied Biomethane. The report has focus on marine transport, such as ferries, but LBM can also be used for heavy duty trucks and trains.

