The UUPO project – New fuels for maritime logistics as drivers of green transition and blue growth

Fuel Info Package: LNG and Methane

samk

Satakunta University of Applied Sciences

SATAKUNTALIITTO

Regional Council of Satakunta

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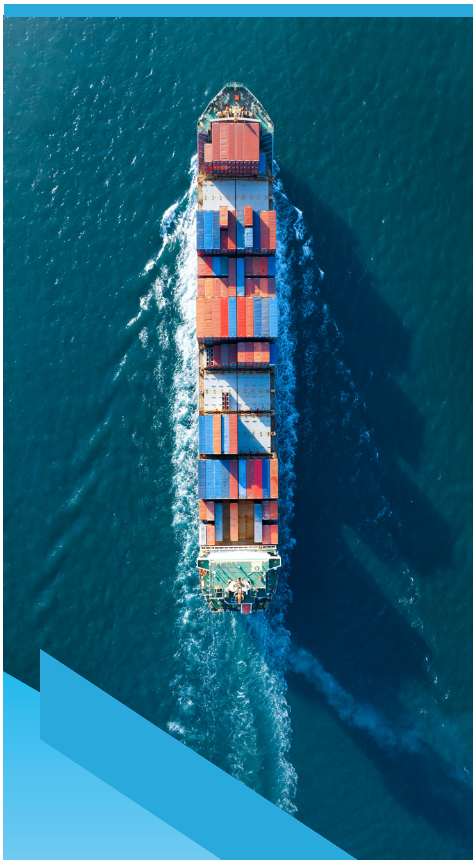
Basic information



Important notes:
1. LNG is the fastest-growing alternative fuel

2. The use of conventional LNG generates the same or even higher greenhouse gas emissions compared to other fossil fuels

3. LNG produces minimal SOx and particulate matter emissions, and its NOx emissions are approximately 90 % lower than those from traditional marine fuels

4. Bio-LNG and e-LNG can be utilized as drop-in fuels in existing LNG vessels

5. There is already a significant amount of infrastructure built for natural gas, facilitating the broader adoption of conventional LNG, as well as bio-LNG and e-LNG in maritime applications

LNG and methane

LNG, or liquefied natural gas, primarily consists of methane (approximately 85–95 %). Methane (CH_4) is a hydrocarbon compound made up of one carbon atom and four hydrogen atoms.

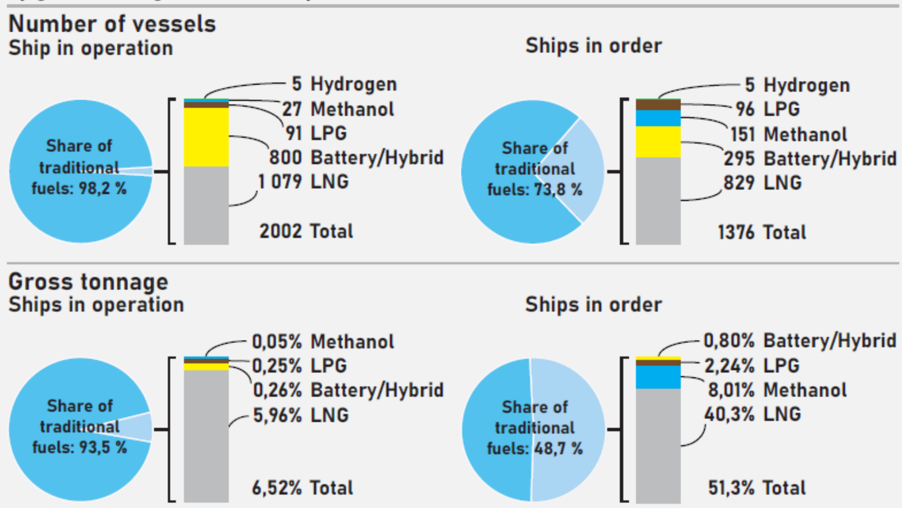
In recent years, the use of LNG has increased significantly, particularly in the maritime sector. This growth is reflected in the order book, as DNV's 2023 report indicates that up to 60% of all vessels ordered, which use alternative fuels, are LNG-powered. [1]

The rise of liquefied natural gas can be attributed in part to its environmentally friendly characteristics compared to traditional fossil fuels, such as heavy fuel oil and diesel. When burned, LNG produces significantly lower emissions of NOx, SOx, and particulate matter, thereby helping to reduce air pollution caused by shipping. [2]

The potential of traditional LNG to reduce greenhouse gas emissions in maritime logistics has also been widely reported. However, recent studies have shown that its use may actually worsen climate change. The main reasons for this are the fugitive methane emissions that occur during the production and use of LNG, as well as unburned methane released from ship engines into the atmosphere. [3] Fugitive emissions refer to emissions that arise from uncontrolled sources, such as pipeline leaks and other similar situations.

Shipping companies that use liquefied natural gas in their vessels can partially avoid the methane emissions generated during fuel production by using bio- or synthetic LNG, which have significantly lower lifecycle emissions than traditional LNG produced from natural gas. [4]

Figure 1. Adoption of alternative fuels in the global fleet by the number of vessels (top) and by gross tonnage (bottom), July 2023



Citations: [1], [2], [3], [4], [Figure 1]

Production methods

Typically, LNG is classified as a fossil fuel because it is produced from natural gas. This fossil LNG is referred to as either gray LNG or blue LNG if the greenhouse gas emissions generated during the production process have been prevented from entering the atmosphere. However, there are more sustainable alternatives to gray and blue LNG, such as bio-LNG and synthetic LNG (e-LNG). These sustainable alternatives are collectively known as green LNG and produce significantly fewer emissions over their lifecycle compared to LNG derived from fossil sources. [5]

Gray LNG

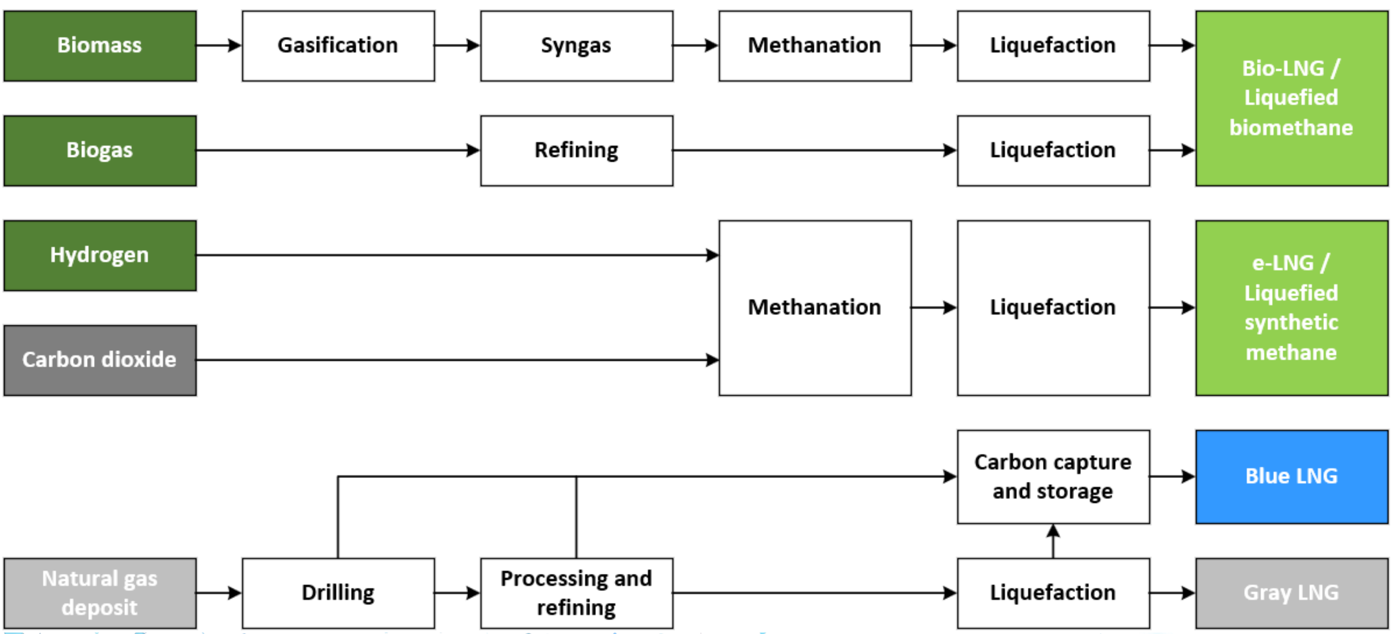
Gray LNG is produced by drilling natural gas from underground natural gas deposits. Natural gas can also be found in association with oil deposits. Depending on the deposit, various drilling methods are used, such as conventional drilling or hydraulic fracturing. In conventional drilling, drill bits penetrate the layers of soil, while in hydraulic fracturing, water and chemicals are injected under pressure into the ground, fracturing the rock formation and releasing natural gas. The choice of drilling method depends on factors such as the depth and composition of the natural gas deposit. After the drilling phase, natural gas is extracted from the deposit and is usually transported via pipelines to production or processing facilities, where it is purified and separated from other substances. The purified natural gas can then be liquefied, making it easier to transport and store. [6]

The production of gray LNG generates significant greenhouse gas emissions, as gaseous natural gas can easily escape into the atmosphere during the drilling and transportation phases. [7] In addition, production facilities emit many other pollutants that are harmful to the local environment and the communities and people living in the area. [8]

Blue LNG

Blue LNG is produced in the same way as gray LNG, but the greenhouse gas emissions generated during the production process are partially prevented from entering the atmosphere through various technological

Figure 2. The main methods for producing LNG and other methane-based fuels



Production methods

solutions. Examples of these include carbon capture, where the generated emissions are captured and stored in geological repositories. The captured carbon dioxide can also be utilized in various processes, such as the production of synthetic fuels.

The problem with blue LNG is that a significant portion of the captured carbon dioxide is currently used for enhanced oil recovery (EOR) methods. In this process, the captured carbon dioxide is injected into oil deposits to increase oil production from that well. This issue affects all "blue" new fuels, but it is particularly significant in the case of blue LNG because natural gas may be produced from the same wells as oil. This means that while the use of blue LNG can significantly reduce greenhouse gas emissions compared to conventional fuels, its environmental benefits can be questioned because carbon dioxide is returned to the atmosphere as a result of enhanced oil production. [9]

Green LNG

Green LNG can be broadly categorized into two different categories: bio-LNG and synthetic or e-LNG. The abbreviations LBM (Liquified Biomethane) and LSM (Liquified Synthetic Methane) are also used. Green LNG can be used in the same way as traditional fossil-based LNG, thereby reducing the use of fossil fuels and the greenhouse gas emissions they produce. [10]

Bio-LNG is produced in several different ways, but the most common method is from biogas. The raw materials for biogas include various biomass sources such as agricultural residues, organic waste, wastewater, and energy crops. The production of biogas begins with the shredding of bio-waste, which is then mixed with water. After mixing, the bio-waste is transferred to silos, where it undergoes an anaerobic fermentation process, meaning it decomposes in an oxygen-free environment due to the action of microbes and heat. The fermentation process produces biogas, which mainly consists of methane, carbon dioxide, and small amounts of other gases. In addition to biogas, the digestion process produces digestate, which can be

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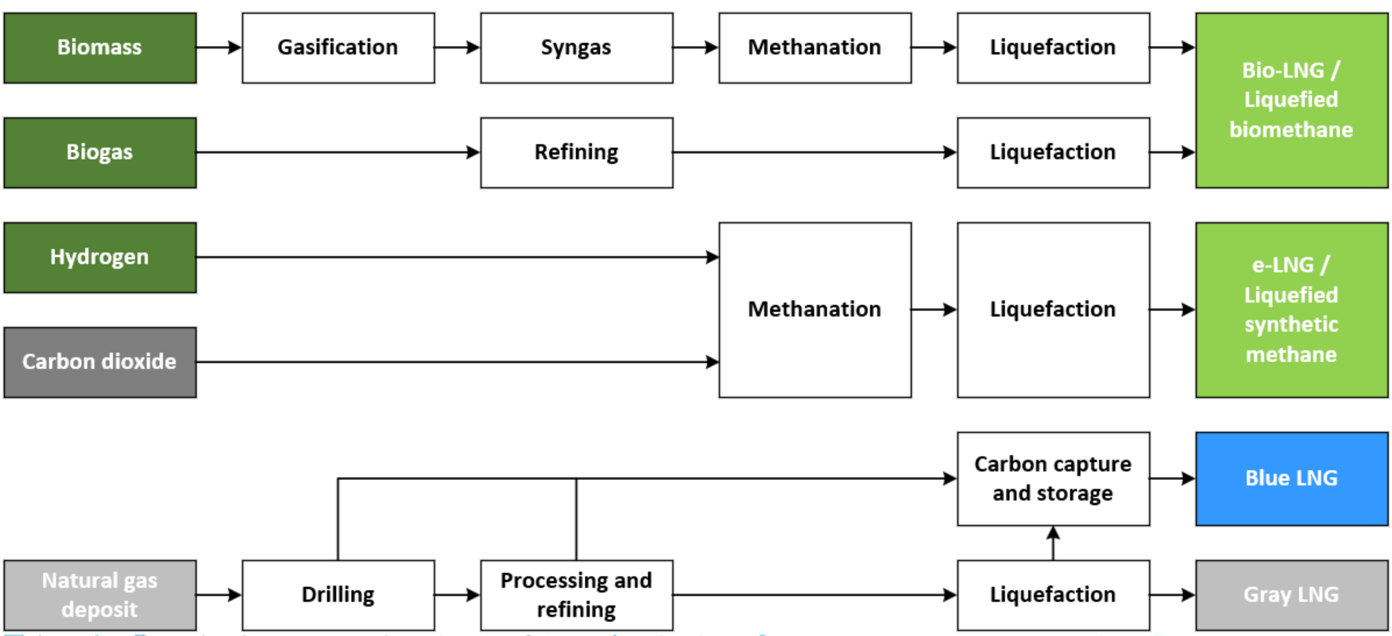

Citations: [9], [10], [Figure 2]

Production methods

used, for example, in fertilizer production. The methane content of biogas is typically around 45–75 %, so other gases and impurities are separated from it, resulting in biomethane, which is compositionally nearly identical to fossil natural gas. The finished biomethane can be used as is or liquefied to produce bio-LNG. Landfills also produce biogas when municipal waste decomposes, and this can be captured using landfill gas collection systems. [11]

Another method for producing biomethane is biomass gasification. In biomass gasification, for example, wood-based biomass is heated in a low-oxygen and high-pressure environment to produce syngas, which mainly consists of carbon monoxide and hydrogen. This produced syngas is purified and processed, after which it is transferred to a methanation reactor. In the reactor, the carbon monoxide and hydrogen from the syngas react with each other, resulting in biomethane. [12]

About 90 % of the produced biomethane is made from biogas. [13] It is worth noting that depending on the source, methane produced from biomass gasification is sometimes classified as synthetic methane.

The production methods for synthetic methane differ quite a bit from those for biomethane. Typically, the production of synthetic methane is based on the combination of hydrogen and carbon dioxide using a catalyst. This type of methane can have very low life cycle emissions if the hydrogen used in its production is generated sustainably, such as through renewable energy sources and electrolysis. Carbon dioxide, on the other hand, does not need to be produced directly; it can be captured, for example, from the flue gases produced by local industries. [14]

The catalyst for the methanation process of synthetic methane can be a traditional metal catalyst, but the process can also be based on biological catalysis, where microorganisms produce methane from carbon dioxide and hydrogen. In this case, it is called biocatalytic methanation. [15]

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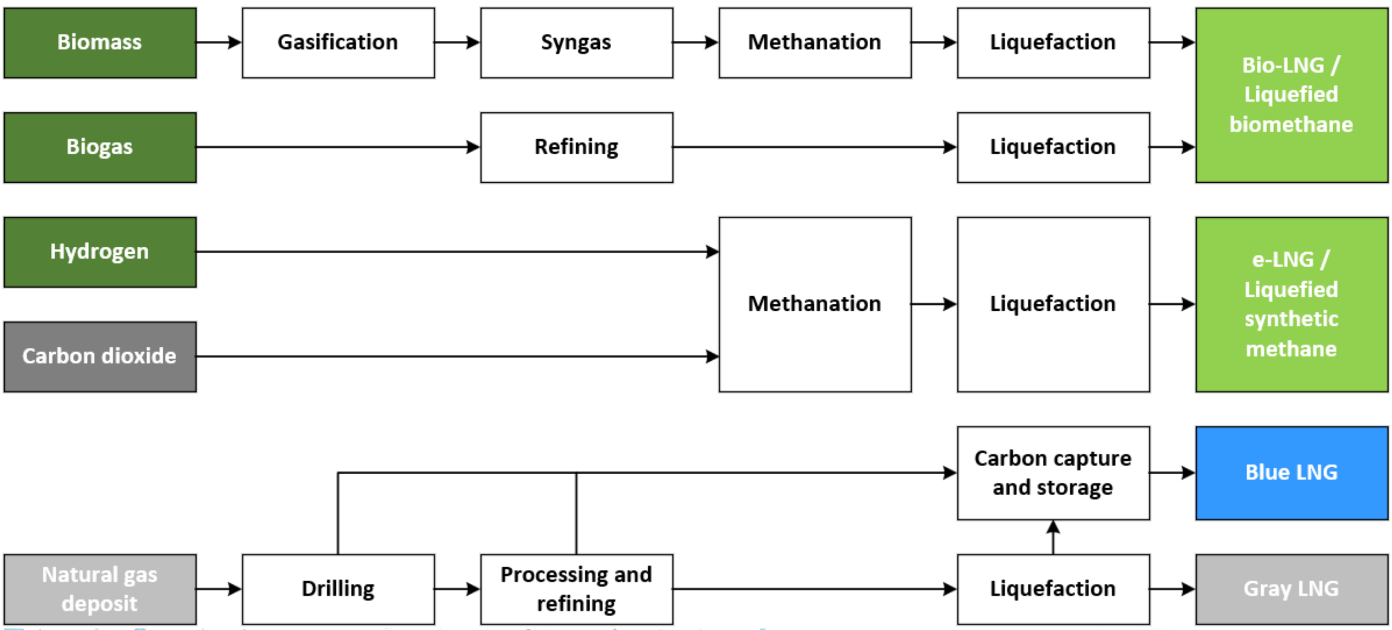

Citations: [11], [12], [13], [14], [15], [Figure 2]

Properties and safety aspects

Fuel properties

The heating value of liquefied natural gas is the second highest among all traditional and alternative maritime fuels, right after hydrogen. However, due to its low density, its volumetric energy density is lower than that of other fossil fuels. As a result, LNG requires about double the space compared to heavy fuel oil. [16]

Before LNG can be effectively utilized in a ship's internal combustion engine, it must first undergo a process where it is vaporized back into a gaseous form and then pressurized to the appropriate level to ensure optimal performance for the engine. [17]

Safety aspects

Liquefied natural gas does not burn in its liquid form as it must first be vaporized and mixed with air in order to ignite. However, in its gaseous form, it spreads quickly into the environment, making it difficult to manage situations in the event of a leak or fire. [18]

In its gaseous state, LNG is not toxic to humans, but in enclosed spaces, it can displace oxygen like other gases, thus posing a suffocation hazard. To minimize this risk, it is important to ensure adequate ventilation and to use appropriate gas detectors that can detect oxygen deficiency in time. These measures can also reduce the risks associated with the fire safety of gas-diluted LNG. [19]

LNG use involves other hazards as well. In particular, the extremely low temperature of LNG can cause frostbite and other cold injuries to individuals handling it. Various material damages are also possible during leaks. Major accidents can be avoided by training personnel and using materials in critical areas that can withstand the effects of LNG's low temperature. Additionally, various contingency measures may be necessary, for example during bunkering, to ensure that LNG does not cause additional damage to the ship's hull or other parts and that the safety of the bunkering personnel is not threatened. [20]

	Energy and storage					Flammability		
Fuel	Density [kg/m^3]	Lower heating value [MJ/kg]	Energy density [MJ/m^3]	Boiling point [°C]	Fuel volume requirement vs. LSHFO	Autoignition temperature in air [°C]	Flashpoint [°C]	Flammability limits in air [%]
LSHFO	993	40,5	40 217	> 180	-	230	> 60	0,6 - 7,5
MDO	819	40,5	33 170	> 180	1,21	210	> 60	0,6 - 7,5
LNG	**450**	**49,1**	**22 095**	**-162**	**1,82**	**540**	**-188**	**5,0 - 15,0**
MeOH	792	19,9	15 761	65	2,55	464	12	6,7 - 36,0
EtOH	789	26,8	21 145	78	1,90	365	17	3,3 - 19,0
L NH_3	680	18,6	12 648	-33	3,18	651	132	15,0 - 28,0
L H_2	70	120	8 400	-253	4,79	585	-	4,0 - 75,0
FAME	880	37,2	32 736	> 180	1,23	261	> 61	0,6 - 7,5
HVO	780	44	34 320	> 180	1,17	204	> 61	0,6 - 7,5
FT-Diesel	785	43,2	33 912	> 180	1,19	204	89	0,6 - 7,5

Citations: [16], [17], [18], [19], [20], [Table]

Production

Global production

Global LNG trade has increased significantly in recent years, with nearly 400 million tons traded in 2022, representing an increase of about 7 % compared to the previous year. In 2022, Australia, Qatar, and the United States accounted for a total of 60 % of the world's LNG exports. [21] The growth in LNG trade is also reflected in the liquefaction capacity of natural gas, which has increased by about 40 % between 2010 and 2022. [22]

The primary reason for the growth of LNG has been its expanded use in various applications, but the war between Russia and Ukraine has also impacted Europe's LNG trade. The conflict has created uncertainty regarding Russian natural gas supplies and increased Europe's interest in LNG as an alternative energy source. This is particularly evident in the growth of LNG imports, with less than 80 million tons imported to Europe in 2021, while the figure rose to 121 million tons the following year. [23]

The use of LNG is expected to continue to grow, with Shell estimating that by 2040, the global demand for LNG will reach around 625–685 million tons. [24]

Although the production of bio- and e-methane is expected to grow rapidly in the coming years, their use in maritime applications is still limited by factors such as the availability of raw materials, production costs, production capacity, and competition from other sectors. Approximately 7,4 billion cubic meters of biogas were produced in 2022, with Europe accounting for about 4 billion cubic meters. [25] According to estimates from the European Biogas Association, biogas production in Europe could reach up to 35 billion cubic meters by 2030, but this amount will not be sufficient, as Europe used around 340 billion cubic meters of natural gas in 2022. [26][27]

The production of e-LNG was practically zero globally in 2020, but new facilities and projects are planned and under construction around the world, indicating that e-LNG production is expected to grow significantly in the coming years. [28]

Future outlooks in Finland and Satakunta

In 2020, energy consumption in Finnish waterborne traffic was approximately 1,75 TWh, while energy consumption in foreign traffic in Finnish economic waters was 6,7 TWh. [29] If these energy needs were to be met with biogas, Finland's biogas production would need to multiply significantly, as the amount of biogas produced in Finland in 2022 was about 0,21 TWh. However, biogas production is expected to rise rapidly, with over 40 biogas and biomethane production facilities planned and under construction in Finland between 2024 and 2027. The total production capacity of these new facilities is 1,2 terawatt-hours, with over 90 % being biomethane. A significant portion of the biomethane produced at these facilities is intended to be liquefied and subsequently used in heavy and maritime transport. [30]

The future of bio- and synthetic methane in Satakunta looks promising. For example, BioEnergo Oy is planning a bioconversion facility in Meri-Pori that would produce both bioethanol and biomethane. [31]

On the other hand, synthetic methane is set to be produced by Q Power in Harjavalta starting in 2024. This operation will take place at P2X Solutions' green hydrogen production facility, and the carbon dioxide required for the methanation process will be sourced from nearby companies and industries. [32]

Citations: [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32]

Technical aspects

Infrastructure, transporation and storage

Methane-based fuels offer several advantages from an infrastructure perspective compared to other new fuels. For example, in Finland, there is already considerable knowledge and experience regarding LNG bunkering, making the process reliable and efficient. Gasum, in particular, has a long history in LNG bunkering, having conducted the first LNG bunkering in the entire Baltic Sea region in 2012. [33]

Additionally, all methane-based fuels can be transported in gaseous form through the existing gas pipeline network. Finland's natural gas transmission network spans approximately 1 200 kilometers, primarily running through various regions of Southern Finland, although part of the pipeline is also located in Pirkanmaa. The transmission network connects to the Baltic countries via the Balticconnector gas pipeline, which runs beneath the Gulf of Finland between Inkoo and Estonia's Paldiski. Finland's natural gas transmission network is also connected to Russia's transmission network in Imatra. [34] There are about one million kilometers of natural gas transmission networks in use worldwide. [35]

Methane-based fuels can also be transported in liquid form, allowing their use in areas where gas pipelines are unavailable. Larger quantities of liquid methane or natural gas are typically transported by sea using LNG carrier vessels. These vessels have varying capacities, with larger carriers able to transport about 120 000 to 260 000 cubic meters of LNG. [36] However, these vessels require a specialized LNG terminal where the cargo can be unloaded. LNG terminals can be found in Finland, including in Hamina, Tornio, and Pori. There is also an LNG terminal ship in Inkoo, where LNG can be stored and re-vaporized back into gas. Among these terminals, Hamina and Inkoo are connected to the natural gas transmission network. [37] LNG terminals can also be used for bunkering fuel for vessels that use liquefied natural gas as their power source.

For shorter distances and smaller quantities, liquid methane and natural gas can be transported using tank trucks. [38]

Storing LNG is relatively challenging, as it requires a storage temperature of about -163 °C to maintain its liquid density. Therefore, it must be stored in insulated cryogenic tanks that continuously cool the LNG and keep its temperature below the boiling point. During storage, some of the liquefied natural gas may vaporize, which can lead to fugitive emissions. These emissions can enter the atmosphere through various means, including valves or junctions in pipelines. Vaporization may occur due to temperature rises in the tank, which can happen due to insulation failure, cooling system malfunctions, or variations in external temperatures. Additionally, various pumps may raise the temperature of the pumped LNG, leading to vaporization. [39]

Fugitive emissions also occur when LNG carrier vessels unload their cargo into terminal tanks, which can result in significant methane emissions into the atmosphere, and this is an important consideration when assessing LNG's environmental impacts. [40]

Citations: [33], [34], [35], [36], [37], [38], [39], [40]

Technical aspects

Use as fuel

The importance of LNG in maritime transport began to grow in the 2010s, and in recent years, its role in the global merchant fleet has further developed. An increasing number of shipping companies have started to invest in LNG-powered vessels or to convert existing ships to be compatible with LNG. Consequently, LNG technology has advanced significantly, and the practices and regulations surrounding it have developed substantially. [41]

This growth has led to LNG becoming the most popular alternative fuel in maritime transport, with its popularity expected to continue as a growing trend. This is clearly reflected in the order books of shipyards. In July 2023, there were 5,252 vessels on order, of which 1,376 were ships using alternative fuels, and among these, 829 were LNG vessels. Currently, about 1% of existing vessels use LNG as their power source. [42]

The growth of LNG over the past decade is also evident in the increase in the number of LNG bunkering vessels, which numbered fewer than five globally in 2013, while in 2023, this number had risen to 35. [43]

The rapid growth in maritime transport can be explained by the fact that many emissions can be significantly reduced with LNG compared to traditional fuels. In particular, emissions of NOx, SOx, and particulate matter are considerably lower than those from traditional fossil fuels. Furthermore, natural gas production has nearly doubled in the past 25 years, which also explains its broader use in various applications. [44]

Due to the high technological maturity of LNG, practically all major marine engine manufacturers offer LNG engines. However, the Finnish company Wärtsilä has been at the forefront of LNG engine development. A particularly significant project in this regard was the conversion of the Bit Viking tanker to LNG power in 2011. This was the first time that heavy fuel oil was replaced with LNG in a maritime vessel. [45]

It is also worth noting that LNG can be used in fuel cells, but this technology still requires further development and investment before it can become a more widely used alternative.

Citations: [41], [42], [43], [44], [45]

Environmental aspects

The use of LNG in maritime transport offers some environmental benefits compared to traditional fuels. For example, LNG produces about 90 % fewer NOx emissions than conventional fuels. LNG also produces almost no SOx or particulate matter emissions. [46] However, it is important to note that there is a significant difference in greenhouse gas emissions depending on whether ships use LNG or greener alternatives such as bio-LNG or e-LNG. This is because natural gas production generates significant greenhouse gas emissions. Additionally, the production process may cause numerous other environmental problems, depending on the drilling methods, production processes, and emission management. [47]

Greenhouse gas emissions

There is much conflicting information regarding the greenhouse gas emissions caused by LNG. Many companies, for example, advertise that using LNG produces fewer carbon dioxide emissions than traditional fuels, which is true, but it is essential to consider the total emissions and their impact on the climate. Methane emissions related to the production, transport, and use of LNG reduce the environmental friendliness of this fuel, as methane is a potent greenhouse gas. Compared to carbon dioxide, methane is about 80 times more potent as a greenhouse gas over a 20-year period and about 30 times more potent over a 100-year period. [48]

Methane emissions occur at various stages of natural gas production, and their monitoring typically falls under the responsibility of natural gas producers. This means that not all leaks may be reported immediately or at all, as these companies may have financial incentives to minimize reported emissions. For example, in 2023, U.S. natural gas producer Phillips 66 did not report a gas leak, which only became more widely known when external researchers published images taken using measurement instruments from the International Space Station. [49]

In addition to fugitive emissions, one of the common issues with LNG use on ships is the release of unburned fuel into the atmosphere along with exhaust gases. This phenomenon is commonly known as methane slip. The IMO and the EU have set the default values for unburned methane in LNG vessels at 3,5 % and 3,1 %, but a recent study by the ICCT, which measured methane levels in ship exhaust gases, found that the actual average was over 6 %. [50] The European organization Transport & Environment estimated in 2016 that LNG vessels with a methane slip of 3,5 % would produce about 0,3–9,0 % more lifecycle emissions than ships using MGO or heavy fuel oil. [51] The ICCT study recommended that policymakers raise the default values to reflect real-world figures so that LNG can be more accurately assessed as an alternative fuel for the future. [52]

The ICCT also published a study in 2020, concluding that LNG use in ships does not contribute to combating climate change, primarily due to fugitive emissions and the methane slip phenomenon. The study emphasized that LNG usage does not support the IMO's goals for reducing greenhouse gas emissions, and in the short term, LNG use may actually worsen climate change compared to traditional fossil fuels. [53]

In contrast, the use of bio- and e-LNG can help reduce greenhouse gas emissions compared to traditional fuels because their production generates significantly fewer emissions. Additionally, using manure in the production of bio-LNG can reduce emissions that would otherwise occur if the manure decomposed naturally. These types of alternatives provide more sustainable solutions that can help mitigate the environmental impact of maritime transport in the long term. [54]

Citations: [46], [47], [48], [49], [50], [51], [52], [53], [54]

Summary

LNG is currently the most widely used alternative fuel in maritime transport. Most of the LNG used is fossil-based, and its production and use generate significant greenhouse gas emissions. The magnitude of the lifecycle emissions caused by LNG is particularly influenced by fugitive emissions that occur during the production, transportation, storage, and bunkering of LNG. Another significant source of emissions is the release of unburned methane from ship engines into the atmosphere. Efforts are ongoing to reduce these emissions in order to minimize the environmental impact of LNG use.

Fugitive emissions are being addressed by upgrading or repairing leaking natural gas pipelines and improving leak detection systems. The formation of unburned methane, on the other hand, is being reduced through research and development focused on optimizing ship engines and exhaust gas treatment technologies.

The main development areas include improving combustion processes, optimizing combustion chambers, and refining exhaust gas treatment systems.

If fugitive emissions and the release of unburned methane can be significantly reduced, the future of LNG in greener maritime transport looks promising, as LNG offers several advantages over traditional fuels. LNG produces significantly fewer SOx, NOx, and particulate matter emissions than conventional fossil fuels. Moreover, the production and use of bio- and e-LNG are increasing, offering even more sustainable alternatives to meet the energy needs of maritime transport. An added benefit of bio- and e-LNG is that the existing natural gas pipeline network can also be utilized for the transmission of these green fuels.

Strengths

+ LNG is already widely used in maritime transport, improving bunkering opportunities and ensuring that established safety protocols are in place for its secure use
+ Bio- and e-LNG can be produced with a very small carbon footprint
+ Energy density is higher than that of many other new fuels
+ Bio- and e-LNG can be directly fed into the natural gas transmission network and used in LNG-powered vessels
+ Natural gas already has a lot of built infrastructure
+ It does not pose a poisoning risk to humans
+ The environmental impact of leaks on nearby ecosystems is relatively small compared to some other fuels

Weaknesses

- LNG generates significant methane emissions over its lifecycle due to fugitive emissions and unburnt fuel
- It is a carbon-based fuel, meaning its use results in CO2 emissions
- The majority of currently used LNG is fossil-based
- It must be stored at extremely low temperatures
- Its energy density is lower than that of fossil fuels
- The production of blue LNG may increase oil production
- The availability of bio- and e-LNG could be affected by demand from other sectors

References

[1] DNV. (2023). Energy transition outlook 2023: Maritime forecast to 2050. (p. 24). Retrieved 23.05.2024 from: https://www.dnv.com/maritime/publications/maritime-forecast-2023/download-the-report/

[2] DNV. (n.d.). LNG as marine fuel. Retrieved 19.06.2024 from: https://www.dnv.com/maritime/insights/topics/lng-as-marine-fuel/environmental-performance/

[3] Pavlenko, N., Comer, B., Zhou, Y., Clark, N., & Rutherford, D. (2020). The climate implications of using LNG as a marine fuel. (pp. 1-2). Retrieved 19.06.2024 from: https://theicct.org/sites/default/files/publications/LNG%20as%20marine%20fuel,%20working%20paper-02_FINAL_20200416.pdf

[4] Lam, J. S. L., Piga, B., & Zengqi, X. (2022). Role of bio-LNG in shipping industry decarbonisation. (pp. 13-14). Retrieved 19.06.2024 from: https://safety4sea.com/wp-content/uploads/2022/10/Sea-LNG-Role-of-bio-LNG-in-shipping-industry-decarbonisation-2022_10.pdf

[5] Macdonald, F., & Martin, D. (n.d.). The maritime alternative fuels barometer: Understanding the maritime industry's pathway to a net-zero future. (p. 29). Retrieved 19.06.2024 from: https://thetius.com/wp-content/uploads/2024/01/Thetius-Maritime-Alternative-Fuels-Barometer.pdf

[6] Department of Energy. (n.d.). Conventional Natural Gas Production. Retrieved 19.06.2024 from: https://afdc.energy.gov/fuels/natural-gas-conventional

[7] Sotoodeh, K. (2021). Fugitive emissions from piping and valves. Retrieved 19.06.2024 from: https://www.sciencedirect.com/science/article/pii/B9780323918626000022

[8] Younes, L., & Bittle, J. (2023). 'Death stars on sinking land': How liquefied natural gas took over the Gulf Coast. Retrieved 19.06.2024 from: https://grist.org/energy/louisiana-liquified-natural-gas-terminal-lng-gulf-coast/

[9] Osaka, S. (2023). Companies capture a lot of CO2. Most of it is going into new oil. Retrieved 19.06.2024 from: https://www.washingtonpost.com/climate-environment/2023/10/25/enhanced-oil-recovery-carbon-capture/

[10] Nelissen, D., Faber, J., van der Veen, R., van Grinsven, A., Shanthi, H., & van den Toorn, E. (2020). Availability and costs of liquefied bio- and synthetic methane: The maritime shipping perspective. (p. 5). Retrieved 19.06.2024 from: https://cedelft.eu/wp-content/uploads/sites/2/2021/03/CE_Delft_190236_Availability_and_costs_of_liquefied_bio-_and_synthetic_methane_Def.pdf

[11] International Energy Agency. (2020). Outlook for biogas and biomethane: Prospects for organic growth. (pp. 13-15). Retrieved 19.06.2024 from: https://iea.blob.core.windows.net/assets/03aeb10c-c38c-4d10-bcec-de92e9ab815f/Outlook_for_biogas_and_biomethane.pdf

[12] International Energy Agency. (2020). Outlook for biogas and biomethane: Prospects for organic growth. (pp. 13-15). Retrieved 19.06.2024 from: https://iea.blob.core.windows.net/assets/03aeb10c-c38c-4d10-bcec-de92e9ab815f/Outlook_for_biogas_and_biomethane.pdf

References

[13] International Energy Agency. (n.d.). An introduction to biogas and biomethane. Retrieved 23.05.2024 from: https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/an-introduction-to-biogas-and-biomethane

[14] SEA-LNG. (n.d.). Liquefied e-methane fact sheet. Retrieved 10.09.2024 from: https://sea-lng.org/wp-content/uploads/2024/06/24-06-07_Liquefied_E-methane_Fact_Sheet_May24_FINAL100.pdf

[15] Q Power. (n.d.). Teknologia: Biokatalyyttinen metanointi. Retrieved 23.05.2024 from: https://qpower.fi/fi/teknologia/

[16] Bertagna, S., Kouznetsov, I., Braidotti, L., Marino, A., & Bucci, V. (2023). A Rational Approach to the Ecological Transition in the Cruise Market: Technologies and Design Compromises for the Fuel Switch. (p. 4). Retrieved 23.05.2024 from: https://www.researchgate.net/publication/366818830_A_Rational_Approach_to_the_Ecological_Transition_in_the_Cruise_Market_Technologies_and_Design_Compromises_for_the_Fuel_Switch

[17] Chorowski, M., Duda, P., Polinski, J., & Skrzypacz, J. (2015). LNG systems for natural gas propelled ships. (p. 1). Retrieved 23.05.2024 from: https://iopscience.iop.org/article/10.1088/1757-899X/101/1/012089/pdf

[18] Cotta, W. K., Haugh, W. A., & Franklin, L. (n.d.). Liquefied Natural Gas as Fuel Design Considerations. (p. 3). Retrieved 23.05.2024 from: https://www.dco.uscg.mil/Portals/9/DCO%20Documents/5p/LGCNCOE/docs/LNGF-DesignConsiderations.pdf?ver=2019-09-11-142443-480

[19] Cotta, W. K., Haugh, W. A., & Franklin, L. (n.d.). Liquefied Natural Gas as Fuel Design Considerations. (p. 3-4). Retrieved 23.05.2024 from: https://www.dco.uscg.mil/Portals/9/DCO%20Documents/5p/LGCNCOE/docs/LNGF-DesignConsiderations.pdf?ver=2019-09-11-142443-480

[20] Cotta, W. K., Haugh, W. A., & Franklin, L. (n.d.). Liquefied Natural Gas as Fuel Design Considerations. (p. 3). Retrieved 23.05.2024 from: https://www.dco.uscg.mil/Portals/9/DCO%20Documents/5p/LGCNCOE/docs/LNGF-DesignConsiderations.pdf?ver=2019-09-11-142443-480

[21] International Gas Union. (2023). 2023 World LNG report. (pp. 7, 21-22). Retrieved 23.05.2024 from: https://igu.org/resources/lng2023-world-lng-report/

[22] Statista. (2023). Nominal natural gas liquefaction capacity worldwide in selected years from 2010 to 2022. Retrieved 23.05.2024 from: https://www.statista.com/statistics/881905/nominal-liquefaction-capacity-of-natural-gas-worldwide/

[23] Shell. (2023). LNG Outlook 2023. (p. 12). Retrieved 23.05.2024 from: https://www.shell.com/what-we-do/oil-and-natural-gas/liquefied-natural-gas-lng/lng-outlook-2023/_jcr_content/root/main/section_599628081_co/promo_copy_copy/links/item0.stream/1676487838925/410880176bce66136fc24a70866f941295eb70e7/lng-outlook-2023.pdf

References

[24] Rashad, M., Chow, E., & Bousso, R. (2024). Shell expects 50% rise in global LNG demand by 2040. Retrieved 19.06.2024 from: https://www.reuters.com/business/energy/global-lng-demand-seen-rising-more-than-50-by-2040-shell-report-2024-02-14/

[25] Cedigaz. (2023). Global biomethane market 2023 assessment – From ambition to action. Retrieved 19.06.2024 from: https://www.cedigaz.org/global-biomethane-market-2023-assessment-from-ambition-to-action/

[26] European Biogas Association. (n.d.). Breaking Free of the Energy Dependency Trap – Delivering 35 bcm of biomethane by 2030. Retrieved 19.06.2024 from: https://www.europeanbiogas.eu/breaking-free-of-the-energy-dependency-trap-delivering-35-bcm-of-biomethane-by-2030/

[27] Statista. (2023). Natural gas consumption in the European Union from 1998 to 2022. Retrieved 23.05.2024 from: https://www.statista.com/statistics/265406/natural-gas-consumption-in-the-eu-in-cubic-meters/

[28] Comer, B., O'Malley, J., Osipova, L., & Pavlenko, N. (2022). Comparing the future demand for, supply of, and life-cycle emissions from, bio, synthetic, and fossil LNG marine fuels in the European Union. (p. 6). Retrieved 23.05.2024 from: https://theicct.org/wp-content/uploads/2022/09/Renewable-LNG-Europe_report_FINAL.pdf

[29] Vanhanen, J., Pulkkinen, A., Salmi, W., Beniard, M., Järvinen, K., & Lehtomäki, J. (2022). Meriliikenteen vaihtoehtoisten polttoaineiden markkinoiden kehitys ja vaikutukset Suomeen suuntautuvan meriliikenteen kustannuksiin. (p. 30). Retrieved 23.05.2024 from: https://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/164405/LVM_2022_13.pdf?sequence=1&isAllowed=y

[30] Biokaasu 2030. (n.d.). Kotimaista biokaasun tuotantoa voidaan kasvattaa merkittävästi, sillä hyödyntämätöntä syötepotentiaalia on paljon. Retrieved 23.05.2024 from: https://biokaasu2030.fi/

[31] Aluehallintovirasto. (2021). Päätös: Porin biokonversiolaitoksen ympäristölupa ja toiminnan aloittamislupa, Pori. (pp. 11, 17). Retrieved 23.05.2024 from: https://pori.cloudnc.fi/fi-FI/Toimielimet/Kaupunginhallitus/Kokous_1712022/Lausuntopyynto_BioEnergo_Oy_biokonversio(78405)

[32] Elinkeino-, liikenne- ja ympäristökeskus. (2021). Päätös ympäristövaikutusten arviointimenettelyn (YVA) soveltamisesta yksittäistapauksessa, vihreän vedyn tuotantolaitos, Harjavalta. (pp. 2-3). Retrieved 23.05.2024 from: https://www.ymparisto.fi/sites/default/files/documents/P2X%20Solutions%20Oy%2C%20vihre%C3%A4n%20vedyn%20tuotantolaitos%2C%20Harjavalta.pdf

[33] Mattila, T. (n.d.). Suomen LNG verkosto. Retrieved 19.06.2024 from: https://www.kaasuyhdistys.fi/wp-content/uploads/2018/12/Suomen-LNG-terminaali-alkaa-muotoutua-Tommy-Mattila.pdf

References

[34] Gasgrid. (n.d.). Kaasun siirtoverkosto. Retrieved 19.06.2024 from: https://gasgrid.fi/kaasuverkosto/kaasun-siirtoverkosto/

[35] Intrenational Energy Agency. (2023). Global Hydrogen Review 2023. (p. 110). Retrieved 23.05.2024 from: https://iea.blob.core.windows.net/assets/cb9d5903-0df2-4c6c-afa1-4012f9ed45d2/GlobalHydrogenReview2023.pdf

[36] Clarksons. (n.d.). What is an LNG ship? Retrieved 19.06.2024 from: https://www.clarksons.com/glossary/what-is-an-lng-ship/

[37] Energiateollisuus. (n.d.). Ajankohtaista kaasumarkkinoista. Retrieved 19.06.2024 from: https://energia.fi/energiapolitiikka/ajankohtaista-kaasumarkkinoista/

[38] CIMC ENRIC. (n.d.). LNG Tanker Truck. Retrieved 19.06.2024 from: https://www.cimcenric.com/cimc-enric-tag/lng-tanker-truck.html

[39] The American Petroleum Institute. (2015). Liqufied Natural Gas (LNG) Operations: Consistent Methodology for Estimating Greenhouse Gas Emissions. Retrieved 19.06.2024 from: https://www.api.org/~/media/files/ehs/climate-change/api-lng-ghg-emissions-guidelines-05-2015.pdf

[40] Comer, B., Beecken, J., Vermeulen, R., Sturrup, E., Paschinger, P., Osipova, L., Gore, K., Delahaye, E., Verhagen, V., Knudsen, B., Knudsen, J., & Verbeek, R. (2024). Fugitive and unburned methane emissions from ships (FUMES). (p. IV). Retrieved 19.06.2024 from: https://theicct.org/wp-content/uploads/2023/11/ID-64-%E2%80%93-FUMES-ships-Report-A4-60037-FV.pdf

[41] Wärtsilä. (2017). LNG - A future fuel for the maritime industry? Retrieved 19.06.2024 from: https://www.wartsila.com/insights/article/lng-a-future-fuel-for-the-maritime-industry

[42] DNV. (2023). Energy transition outlook 2023: Maritime forecast to 2050. (p. 24). Retrieved 23.05.2024 from: https://www.dnv.com/maritime/publications/maritime-forecast-2023/download-the-report/

[43] International Gas Union. (2023). 2023 World LNG report. (pp. 102-103). Retrieved 23.05.2024 from: https://igu.org/resources/lng2023-world-lng-report/

[44] Statista. (2024). Natural gas production worldwide from 1998 to 2023. Retrieved 23.05.2024 from: https://www.statista.com/statistics/265344/total-global-natural-gas-production-since-1998/

[45] Wärtsilä. (2017). Bit Viking. Retrieved 23.05.2024 from: https://www.wartsila.com/insights/case-study/bit-viking

[46] Aakko-Saksa, P., & Lehtoranta, K. (2019). Ship emissions in the future. (p. 1). Retrieved 23.05.2024 from: https://cris.vtt.fi/ws/portalfiles/portal/24205607/VTT_R_00335_19.pdf

References

[47] U.S. Energy Information Administration. (2024). Natural gas explained. Retrieved 19.06.2024 from: https://www.eia.gov/energyexplained/natural-gas/natural-gas-and-the-environment.php

[48] Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D. J., Mauritsen, T., Palmer, M. D., Watanabe, M., Wild, M., & Zhang, H. (2021). The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity. (2021). The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity. (p. 1017). Retrieved 19.06.2024 from: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter07.pdf

[49] Clark, A., & Mider, Z. (2023). Phillips 66 Failed to Report Big Gas Release Spotted From Space. Retrieved 19.06.2024 from: https://financialpost.com/pmn/business-pmn/phillips-66-failed-to-report-big-gas-release-spotted-from-space?utm_source=ground.news&utm_medium=referral

[50] Comer, B., Beecken, J., Vermeulen, R., Sturrup, E., Paschinger, P., Osipova, L., Gore, K., Delahaye, E., Verhagen, V., Knudsen, B., Knudsen, J., & Verbeek, R. (2024). Fugitive and unburned methane emissions from ships (FUMES). (pp. I-V). Retrieved 19.06.2024 from: https://theicct.org/wp-content/uploads/2023/11/ID-64-%E2%80%93-FUMES-ships-Report-A4-60037-FV.pdf

[51] European Federation for Transport and Environment. (2016). Natural gas in ships: Costs/benefits of LNG versus conventional fossil fuels. (p. 1). Retrieved 19.06.2024 from: https://te-cdn.ams3.digitaloceanspaces.com/files/2015_02_TE_briefing_natural_gas_shipping_FINAL.pdf

[52] Comer, B., Beecken, J., Vermeulen, R., Sturrup, E., Paschinger, P., Osipova, L., Gore, K., Delahaye, E., Verhagen, V., Knudsen, B., Knudsen, J., & Verbeek, R. (2024). Fugitive and unburned methane emissions from ships (FUMES). (pp. I-V). Retrieved 19.06.2024 from: https://theicct.org/wp-content/uploads/2023/11/ID-64-%E2%80%93-FUMES-ships-Report-A4-60037-FV.pdf

[53] Pavlenko, N., Comer, B., Zhou, Y., Clark, N., & Rutherford, D. (2020). The climate implications of using LNG as a marine fuel. (p. 1). Haettu 19.06.2024 from: https://theicct.org/sites/default/files/publications/LNG%20as%20marine%20fuel,%20working%20paper-02_FINAL_20200416.pdf

[54] Lam, J. S. L., Piga, B., & Zengqi, X. (2022). Role of bio-LNG in shipping industry decarbonisation. (p. 13). Retrieved 19.06.2024 from: https://safety4sea.com/wp-content/uploads/2022/10/Sea-LNG-Role-of-bio-LNG-in-shipping-industry-decarbonisation-2022_10.pdf

References for graphs, figures and tables

p.2

Figure 1:
DNV. (2023). Energy transition outlook 2023: Maritime forecast to 2050. (p. 24). Retrieved 23.05.2024 from: https://www.dnv.com/maritime/publications/maritime-forecast-2023/download-the-report/

pp.3-5

Figure 2:
International Energy Agency. (2020). Outlook for biogas and biomethane: Prospects for organic growth. (p. 5). Retrieved 19.06.2024 from: https://iea.blob.core.windows.net/assets/03aeb10c-c38c-4d10-bcec-de92e9ab815f/Outlook_for_biogas_and_biomethane.pdf

U.S. Energy Information Administration. (2023). Natural gas explained. Retrieved 19.06.2024 from: https://www.eia.gov/energyexplained/natural-gas/delivery-and-storage.php

p.6

Table:
Solakivi, T., Paimander, A., & Ojala, L. (2022). Cost competitiveness of alternative maritime fuels in the new regulatory framework. (p. 2). Retrieved 05.06.2024 from: https://www.utupub.fi/bitstream/handle/10024/173681/1-s2.0-S1361920922003261-main.pdf?sequence=1

Bertagna, S., Kouznetsov, I., Braidotti, L., Marino, A., & Bucci, V. (2023). A Rational Approach to the Ecological Transition in the Cruise Market: Technologies and Design Compromises for the Fuel Switch. (p. 4). Retrieved 05.06.2024 from: https://www.researchgate.net/publication/366818830_A_Rational_Approach_to_the_Ecological_Transition_in_the_Cruise_Market_Technologies_and_Design_Compromises_for_the_Fuel_Switch

Xing, H., Stuart, C., Spence, S., & Chen, H. (2021). Alternative fuel options for low carbon maritime transportation: Pathways to 2050. Retrieved 05.06.2024 from: https://www.sciencedirect.com/science/article/pii/S0959652621008714?via%3Dihub

Ampah, J. D., Yusuf, A. A., Afrane, S., Jin, C., & Liu, H. (2021). Reviewing two decades of cleaner alternative marine fuels: Towards IMO's decarbonization of the maritime transport sector. Retrieved 05.06.2024 from: https://www.sciencedirect.com/science/article/pii/S0959652621030675?via%3Dihub

The Engineering ToolBox. (n.d.). Fuels - Higher and Lower Calorific Values. Retrieved 05.06.2024 from: https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

European Commission. (2021). Regulation of the European Parliament and of the Council on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC. (Annex II). Retrieved 05.06.2024 from: https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A52021PC0562

References for graphs, figures and tables

p.6 Table:
Hürpekli, M., & Özsezen, A. N. (2023). Determination of combustion and emission characteristics of liquid Fischer-Tropsch diesel fuel synthesized from coal in a diesel engine. Retrieved 05.06.2024 from: https://www.sciencedirect.com/science/article/pii/S0196890423006970

Nair, A. (2016). Alternative Fuels for Shipping: Potential for reductions in CO2 emissions, Financial viability for ship owners and, Optimised fleet mix design for policymakers. (p. 26). Retrieved 05.06.2024 from: https://www.google.com/url?sa=t&source=web&rct=-j&opi=89978449&url=https://thesis.eur.nl/pub/41180/A.-Nair-Thesis-Final-441409-A.Nair.pdf&ved=2ahUKEwigvu_mga6HAxWBFBAIHcUxDfcQFnoECBYQAQ&usg=AOvVaw-2gONDv_4o4A7a8ZhjFtsD-

Sources of images

p.1 Adobe Stock: Federico Aliaksandr Siamko. (n.d.). Retrieved 30.08.2024 from: https://stock.adobe.com/images/container-cargo-ship-in-the-ocean-at-sunset-blue-sky-background-with-copy-space-nautical-vessel-and-sea-freight-shipping-international-global-business-logistics-transportation-import-export-concept/756026306

p.2 Adobe Stock: Yellow Boat. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/aerial-top-view-of-cargo-ship-carrying-container-and-running-for-export-goods-from-cargo-yard-port-to-custom-ocean-concept-technology-transportation-customs-clearance/483855922

p.3 Adobe Stock: PNG Lover. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/oil-refinery-plant-isolated-on-transparent-background/763105869?asset_id=763105869

p.4 Adobe Stock: PNG Lover. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/oil-refinery-plant-isolated-on-transparent-background/763105869?asset_id=763105869

p.5 Adobe Stock: PNG Lover. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/oil-refinery-plant-isolated-on-transparent-background/763105869?asset_id=763105869

p.6 Adobe Stock: bsd studio. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/preventing-workplace-injury-concept-icons-set-occupational-health-and-safety-idea-thin-line-color-illustrations-isolated-symbols-editable-stroke-roboto-medium-myriad-pro-bold-fonts-used/551487228?asset_id=551487228

p.7 Adobe Stock: Icon-Duck. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/lean-manufacturing-banner-vector-illustration-with-the-icons-of-six-sigma-management-quality-standard-industry-continuous-improvements-reduce-waste-improve-productivity-efficiency-keizen/672171945?asset_id=672171945

p.8 Adobe Stock: Gondex. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/continuous-line-drawing-of-machine-gears-the-concept-of-gears-on-a-single-line-style-machine-machine-gear-technology-concept-in-single-line-doodle-style/566081642?asset_id=566081642

p.9 Adobe Stock: Gondex. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/continuous-line-drawing-of-machine-gears-the-concept-of-gears-on-a-single-line-style-machine-machine-gear-technology-concept-in-single-line-doodle-style/566081642?asset_id=566081642

Adobe Stock: aerial-drone. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/493941813

p.10 Adobe Stock: The Deep Designer. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/638437077?asset_id=638437077

Sources of images

pp.2-20 Adobe Stock: Steves Artworks. (n.d.). Retrieved 09.05.2024 from: https://stock.adobe.com/images/blue-watercolor-sea-wave-texture-design-on-transparent-background/773410060?asset_id=773410060