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Economic incentives and technological limitations govern environmental impact of LNG feeder vessels

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ABSTRACT

In the transition to sustainable shipping, Liquified Natural Gas (LNG), is proposed to play a role, reducing emissions of sulphur and nitrogen oxides, and particulate matter. However, LNG is a fossil fuel and there is an ongoing discussion regarding the extent of methane slip from ships operating on LNG, challenging the assumptions of LNG as a sustainable solution. Here we show another aspect to consider in the environmental assessment of shipping; LNG feeder vessels may spend as much as 25% of their time at sea just running the ship to ensure the pressure in the tanks are not exceeded, i.e., run time not directly attributed to the shipment of gas from one port or ship, to another. In other words, the economic incentives are currently allowing for roughly 32% increase of the ships' operational emissions and discharges and increased navigational risks. Most coastal areas are heavily affected by anthropogenic activities and e.g., in the Baltic Sea there is consensus among the HELCOM member states that the input of nutrient and hazardous substances must be reduced. Even if the LNG feeder vessels are currently few, the possibility to reduce their environmental impact by 32% should be an attractive opportunity for future policy measures and investigation of technological solutions of the problem.

1. Introduction

Although gas pipelines are the backbone of the gas markets, Liquified Natural Gas (LNG) is the preferred hedging option in anticipation of uncertain events, while investigating several possible political scenarios on the European, North American, and Asian gas markets (Fig. 1) Egging and Holz (2016); (Peng et al., 2021). At the end of April 2022, 641 LNG carrier were involved in the global trade and during 2021 almost 350 million tons of LNG were imported in Asia and Europe (International Gas Union, 2022). The relationship between LNG freight costs and natural gas price spreads governs the global trade, which primarily is conducted under LTCs Long-Term, fixed destination contracts, hence the amount of spot trading is growing (Oglend et al., 2016).

Yan et al. (2023) used Automatic Information Systems (AIS) data to study the trading pattern of large LNG tankers importing LNG to China. This study was focused on large scale importing of LNG, however, as discussed by Huijsmans et al. (2015) the LNG trade can also use smaller LNG feeders to transport the LNG regionally, between export and import terminals. The LNG feeders are often contracted both by suppliers and consumers to gather and deliver LNG in a given interval (Geng et al., 2017). This may cause an unbalance as the vessels need to keep the LNG onboard longer than necessary. There may also be pricing differences that could cause a demand to keep LNG onboard the feeders.

Onboard the LNG feeders, the LNG is kept in insulated tanks, close to LNG vaporization temperature, approximate −163 °C. However, even a slight temperature increase will cause LNG to evaporate into natural gas, which during transport is denoted as Boil-Off Gas (BOG). The BOG causes increased pressure in the tanks or an increased temperature. There are generally two options how to handle the BOG; either to consume it as fuel, or to re-liquefy and return it back to the LNG cargo tanks (Park et al., 2021; Yuan et al., 2019). Ships that consume the BOG as fuel need to keep their engines running all the time BOG is produced, which could create economic and operational incentives to remain operating at sea instead of entering port, awaiting the best conditions to unload the cargo. This in turn may result in ships running at sea without contributing to any "essential" transport work in terms of moving cargo from point A to point B but instead increasing the total distance travelled between the points. This perspective is currently not considered in life cycle assessments of LNG. (Al-Douri et al., 2022) reviewed the literature of LNG life cycle GHG emissions and concluded that the results varied depending on several factors, such as shale gas extraction, pre-treatment, pipeline transportation distance, liquefaction plant

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capacity/technology, and ship propulsion system. Further, they concluded that LNG compared to conventional fuels can reduce life cycle emissions up to 18%, in line with the general claim that ships running on LNG have lower environmental footprints compared to ships running on diesel (Jang et al., 2021 and references therein). Since LNG does not contain sulphur, there will not be any sulphur oxide emissions from LNG ships and the emissions of particulate matter (PM) and nitrogen oxide (NO_X) (especially from LNG low pressure dual fuel engines) will also be low (Grönholm et al., 2021). Yet, LNG is of fossil origin and will as such have an impact of the climate, both with respect to carbon dioxide (CO_2) from combustion, and unburned methane (CH_4) also known as methane slip. Methane has significantly higher Global Warming Potential (GWP) than CO_2. When GWP for CO_2 is normalized to 1 over 100 years, CH_4 has a corresponding GWP of 28–36 (Etminan et al., 2016). The methane slip from LNG fuelled ships, especially low-pressure dual fuel engines, can imply a higher climate footprint compared to diesel fuelled vessels (Grönholm et al., 2021). The climate footprint of the shipping industry is today estimated to be around 3% and during the last two decades most research on alternative fuels have focused on LNG (Ampah et al., 2021) and the number of LNG ships are expected to increase rapidly in the coming decades (IMO, 2020). These insights have previously led e.g., Lindstad and Rialland (2020) to stress the importance of adopting policies targeting broader GHG emissions reduction, instead of only focusing on CO_2. Analogously, it is important to include the operational behaviour of LNG ships spending time at sea burning BOG without carrying out "essential" transport work and such assessments should include all operational emissions from the ships.

Beside fuel related emissions, ships give rise to a range of other emissions and discharges (Jalkanen et al., 2021; Ytreberg et al., 2022). Grey water from showers, laundry and kitchen areas contains nutrients, contaminants and cleaning agents and sometimes non-indigenous species such as pathogenic microorganisms. The same types of chemical substances and microorganisms are also found in sewage, also known as black water, which in addition may contain pharmaceutical substances. Most ships have a continuous leakage of propeller shaft lubrication oil. Ship hulls are usually painted with toxic antifouling paints, to prevent biofouling and spreading of non-indigenous species. However, a drawback is that antifouling paints release large amounts of copper (Cu) and zinc (Zn) to the marine environment. Ballast water treatment systems aim at reducing spreading of non-indigenous species, but may also discharge unintentionally produced toxic or carcinogenic by-products such as bromate and bromoform. When assessing the environmental pressure and impacts of ships, all types of emissions and discharges should be included, and beyond operational emissions, the risk of accidents should also be considered. Increased time at sea, will per se increase the risk of ship-ship collisions (Mazurek et al., 2022). The impacts of pressures from ships on the marine environment will depend on the sensitivity of the area. The Baltic Sea is a sensitive brackish sea area, not reaching Good Environmental Status according to the EU Marine Strategy Framework Directive (EC, 2008), with respect to eutrophication nor hazardous substances (HELCOM, 2018). Hence, extensive measures are taken to reduce input of nutrients and hazardous substances to the Baltic Sea (HELCOM, 2021). The motivation for these measures is linked to the great value, related to the blue economy, a healthy marine environment provides humanity (IOC, 2020; OECD, 2016). The input of nutrients and hazardous substances from Baltic Sea shipping has previously been estimated to result in environmental damage costs in the same order of magnitude (1353 million €) as the corresponding impacts on air quality and climate change (1553 million €) (Ytreberg et al., 2021). Although such assessments contain large uncertainties it reinforces the need for holistic assessment of ships' environmental pressures and impacts.

During fall 2022 media reports highlighted that large LNG tankers were postponing to unload their cargo, awaiting higher prices on the natural gas market (e.g., LaRocco and Lori, 2022). These reports implies that ships spend possibly substantial time at sea, beyond expected time needed for transport of LNG from one port to another. A screening exercise (see Appendix A) of AIS data of LNG ships, revealed that some LNG feeder vessels had particularly large share of their time at sea, basically running in circles. Hence, the aim of this work is to study operational behavioural pattern of LNG feeder vessels in Northern Europe and to assess the associated pressure on climate and the marine environment of this circling behaviour.

2. Material and methods

This case study of one LNG feeder vessel's operation is geographically delimited to the North Sea and the Baltic Sea during the time period January 1st, 2021 to December 31st, 2022. The study is based on a combination of AIS-data analysis of vessel movements, and emission factors of GHG and pollutants, based on the concepts developed by Jalkanen et al. (2021). Then, by categorizing the ship's movement patterns (se details in section 2.3), the associated generation of GHG and pollutants not related to "essential" transport work, from here on referred to as "burning BOG", could be calculated.

2.1. LNG feeder vessel characteristics

The case study object is a small-scale LNG feeder vessel, operating in Northern Europe. However, the aim is not to point out a specific ship, why typical ship characteristics of small-scale LNG feeders were retrieved from IHS Fairplay (2023) (Table 1), where the mean values are provided for the current fleet of LNG feeders, consisting of 29 ships, with respect to their design and operational characteristics. The case study vessel is in the upper range of the ship size related parameters (ship length, breadth, max draught, and displacement) compared to the current fleet means. Analogously, the propulsion related parameters (design speed, installed main engine power and maximum tank

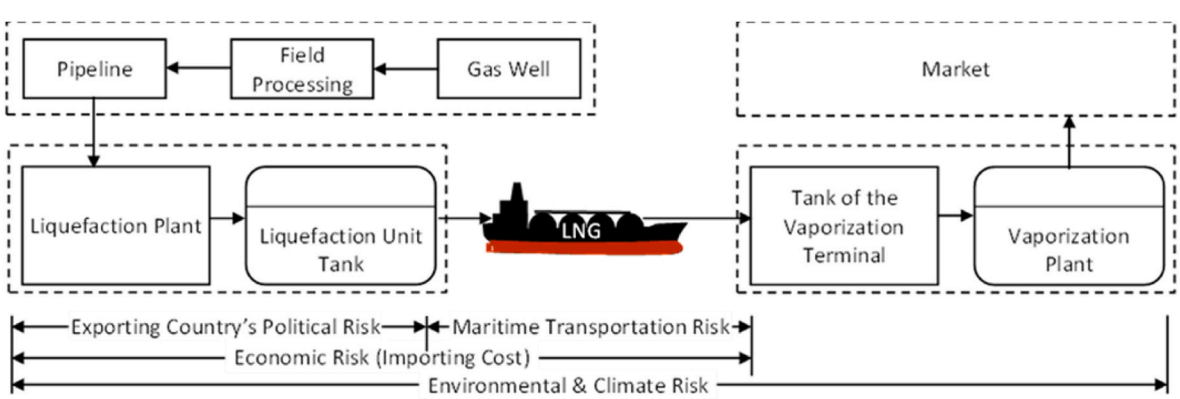

Fig. 1. Different risk aspects in the LNG supply chain starting from exporting countries and ending with importing countries.

Table 1
Typical ship characteristics based of 29 LNG feeders and assumptions used for calculations in the case study. The statistic is generated based on 29 LNG feeders found in the database Sea-web, IHS Fairplay (2023) while the bunker consumption and total CO_2 emission are gathered from the THETIS-MRV database (EMSA, 2023). The actual tank capacity, wetted surface and cabin crew member, which is based on the information above.

	Mean	STDEV	Case study assumptions
Ship length (L_{BP}) m	114.3	28.7	155
Breadth, m	19.1	3.5	22.7
Max draught, m	6.2	1.6	8.2
Displacement, m^3	11 300	5000	19 500
Design speed, knots	13.6	2.3	15.8
Installed main engine power, kW	4850	2620	7800
Maximum gas tank capacity, m^3	8200	5400	15 500
Actual capacity (disregarding 5% heel) m^3	7790		14 725
Annual bunker consumption, m^3	1550	2500	5700
Annual CO_2 emission, m^3	4250	7310	15 800
Wetted surface area, m^2			4540
# Cabin crew			25

capacity) of the case study vessel are higher than the average LNG feeder vessel. With respect to maximum tank capacity in Table 1 it is assumed that only 95% is usually utilized, while the last 5 % is kept as heel, to reduce fatigue caused by temperature shifts (Hasan et al., 2009). The CO_2 emissions are retrieved from the database THETIS-MRV (EMSA, 2023). To allow for calculation of leakage of antifouling paint, the total wetted surface area was calculated from Denny-Murford formula (Equation (1)) (Molland et al., 2017), which is comparable to other formulas available in literature Moser et al. (2016):

$$WSA = 1.7 \times L_{BP} \times T + \frac{\nabla}{T} \tag{1}$$

where WSA is the wetted surface area at maximum summer draft (m^2) L_{BP} is the ship length (m), T is the maximum summer draft (m), and ∇ the volumetric displacement (m^3).

The generation of liquid waste streams grey and black water, and food waste, is related to the number of persons onboard the ship. The number of crew for the case study vessel was assumed to be 25 persons.

2.2. AIS data

To obtain and classify the transport work of one LNG feeder, AIS-data from the crowd sourcing network AISHub, and the national authorities in Norway, Sweden and Denmark was used. Transmitting AIS is a requirement from IMO for all ships above 300 Gross Tonnage since 2002 (Svanberg et al., 2019). The transmitted AIS data are received by shore stations. Ships send out two types of messages; one dynamic and one static type. The Dynamic data (message 1–3) contains information of the ship's position, heading, rate of turn, speed and course over ground. The signal is transmitted from the ship in an interval of 2–10 s depending on its speed and rate of turn. The static message (message 5) contains the IMO number, name, callsign, ship type, overall dimensions, ETA and destination. This message is transmitted once every 5 min. In this study is the information in the dynamic messages was compressed into vector data. How the vector compression is performed is illustrated in Fig. 2, where trailing positions containing a similar speed and course over ground are joined in a vector (Hörteborn et al., 2019). This compression reduces the amount of data by approximate 99% and simplifies the data analysis since trailing position are linked. To analyse the ship's travel pattern, the vectorized AIS data was observed in the opensource Geographic Information Systems software, QGIS.

2.3. Ship activity classification

Oil transportation often involves three types of activities: transportation, loading/unloading or anchoring (Regli and Adland, 2019). When Yan et al. (2023) studied the LNG trading in China they divided their study in three different levels, ship, port and country. However, while categorizing the operational behavioural pattern and the time that the LNG feeder spent in different categories another two categories was added, see Table 2.

To some extent, this categorization activity is a subjective task, for example when does the ship start/stop the transport respective burning BOG activity or how is long periods without AIS data treated? To decrease the subjectivity of the method, the time burning BOG is measured between a similar point for entering and exiting the circle. In the schematic illustration of a ships AIS trajectory in Fig. 3, is the transport work marked in green and burning BOG in orange.

The ship position is sent out at least every 10 s during sailing at sea. However, the base station on land does not recover all messages when the ship is far away. To mitigate this, the position sequence is connected as illustrated in Fig. 2 and trajectories that spans more than 2 h is checked to ensure that the distance, speed and time are matching. Cases that do not match are regarded as unknown time.

The port calls are further split into *import port calls* (when the ship imports LNG and its draught increases) and *export port calls* (when the ship exports LNG and its draught decreases). The unknown time is when the ship has been outside the coast of Lithuania and Estonia where the coverage from the four providers of AIS data used in this article is poor.

2.4. Calculation of GHG, nutrients, copper and stern tube oil emissions

Annual CO_2 emissions related to bunker consumption was estimated from the publicly available THETIS-MRV database. All vessels in Europe

Table 2
Ship activity categories.

Activity	Description
Transport	Ship is moving between two ports
Port	The ship is moored or moving inside a port
Anchored	The ship is stationary outside a port area
Burning BOG	Ship is traveling in circles at operational speed
Unknown	AIS data is missing for the area

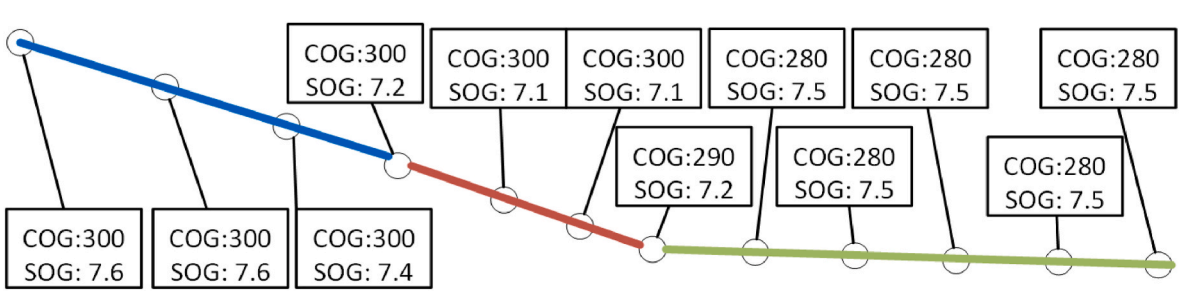

Fig. 2. Twelve fictive positions linked with 3 vectors.

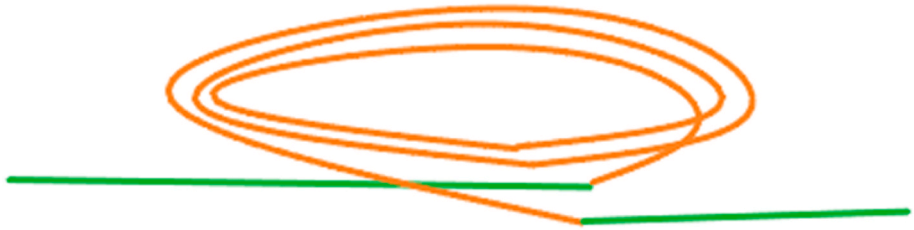

Fig. 3. A schematic illustration of a ships AIS trajectory highlighting the difference between transport (green) and burning BOG (orange) activity. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

have to report to EMSA (2022). Methane emissions were calculated from estimated ratio between CO_2 and CH_4 emissions for low pressure dual fuel engines, 2–4 vol % (or 0.7% −1.5 mass % with regards to the 36 % difference in molecule masses), according to Grönholm et al. (2021). Emissions of nutrients (phosphorus (P), and nitrogen (N)) from sewage, grey water and food waste, copper from antifouling paints, and bilge water, and volume of stern tube oil leakage, were calculated based on the number of days at sea, (from section 2.3 Ship activity classification), ship characteristics (Table 1), combined with the emission factors in (Jalkanen et al., 2021) (Table 3). The ship was assumed to use antifouling paint with Cu(I)oxide with a leakage rate of 24.5 g cm^{-2} d^{-1} (Jalkanen et al., 2021).

To provide a rough estimate of the possible stimulation of cyanobacterial growth from the nutrient loads, Redfield ratio of carbon and phosphorus (C:P = 106) was used to calculate carbon content of microalgae. The carbon content was then applied to a seasonal range of carbon content in volume of cyanobacterial biomass (0.40 and 2.0) μmol $C*L^{-1}$ biomass, based on values reported by Walve and Larsson (2007).

3. Results

The screening analysis of LNG tankers movements in the North Sea and in the Irish Sea during the four last months of 2022, see Appendix 1. During September the ships were sailing to port without stop, but during October and November the tankers changed their behaviour. The tankers slowed down slightly but also stared to sail in circles, which is not part of the normal pattern for large LNG tankers.

3.1. Tracking ships via their AIS data

In depth analysis of the vectorized data of the LNG feeder, used in the case study, shows that it operated in the North Sea, the Skagerrak and the Baltic Sea and that is had small spatiotemporal variations in speed over ground, see Fig. 4. The ship activity was manually categorized in the five categories (Table 2), hour by hour, between Jan 1st, 2021–Dec 31st, 2022. During this period the ship made 68 import port calls and 86 export port calls. A typical example of the category burning BOG is illustrated in the inset in Fig. 4, where the ship is traveling back and forward without making any "real transport work".

The number of hours spent on the different activities are illustrated in Fig. 5. Accounting for some unbalances in the system etc it is assumed that the ship delivered 12 000 m^3 each time. Using these assumptions, the ship delivered roughly 800 000 m^3 LNG during the two years studied time period.

Excluding the hours attributed to the category Unknown time, the ship sailed (transport + burning BOG) for roughly 11 650 h, of which almost 3700 h, or 32 % of the time, were spent on burning BOG. The transport pattern in terms of speed distribution and share that the ship spent in the BOG category, looks similar during the two years studied, indicating that the ship annually spends 1850 h on burning BOG. Combining this with the consumption, results in that 1840 m^3 per year is consumed when the ship is running in circles. This consumption corresponds to almost 0.5 % of the assumed total transported the LNG (400 000 m^3) during the short sea transport.

Table 3
Estimated average daily emissions of GHG, nutrients, copper and stern tube oil from a LNG feeder vessel.

Average daily emission						
Onboard Source	CO_2 (metric t)	CH_4 (metric t)	P (g/person)	N (g/person)	Cu (g)	Oil (L)
Combustion	43.5					
Unburned		0.39–0.78				
Sewage			1.6	16		
Grey water			1.9	4.4		
Food waste			0.5	1.7		
Antifouling paint					1111	
Bilge water					0.002	
Stern tube oil						1

3.2. Emissions

The estimation of the daily emissions was presented in Table 3. Multiplying these figures with the number of days that the LNG feeder spent in the vessel activity category BOG (3700/24) gives the estimated annual emissions. This corresponds to gaseous emissions of CO_2 and CH_4, 2150 and 90 metric tonnes, respectively. The corresponding estimated annual input of copper from antifouling paints and bilge water was 169 kg and the volume of stern tube oil was 76 L. The estimated annual emissions of nutrients during vessel operation in the activity category BOG were 7.6 kg of phosphorus and 42 kg of nitrogen, which could possibly stimulate a cyanobacterial bloom with a volume of 1000–50 000 m^3.

4. Discussion

LNG is assumed to play a role in the transition to sustainable shipping, although concerns have been raised that LNG is a fossil fuel, and special concern about the methane slip that may imply that LNG fuelled ships have higher climate footprint than diesel fuelled ships (Grönholm et al., 2021; Jang et al., 2021; Lindstad and Rialland, 2020). Jang et al. (2021) also stress the importance of large data sets on LNG ships' environmental and climate impact performance, questioning the usefulness of case studies on individual ships. Although it is correct that there are large uncertainties in assessments based on emission factors, and large variations among individual ships, the present case study illustrates a relative comparison of the emissions associated with BOG activity, in relation to "real" transport work. Hence, the case study highlights a previously overlooked aspect of LNG ships' environmental and climate impact performance attributed to BOG activity, which tend not to be distinguished in LCAs of LNG ships (Jang et al., 2021). If AIS data is used to assess ship emissions per transport work (e,g, CO_2 emissions per ton km) and BOG activity is not distinguished, the efficiency of the transport work will be overestimated, i.e., the total

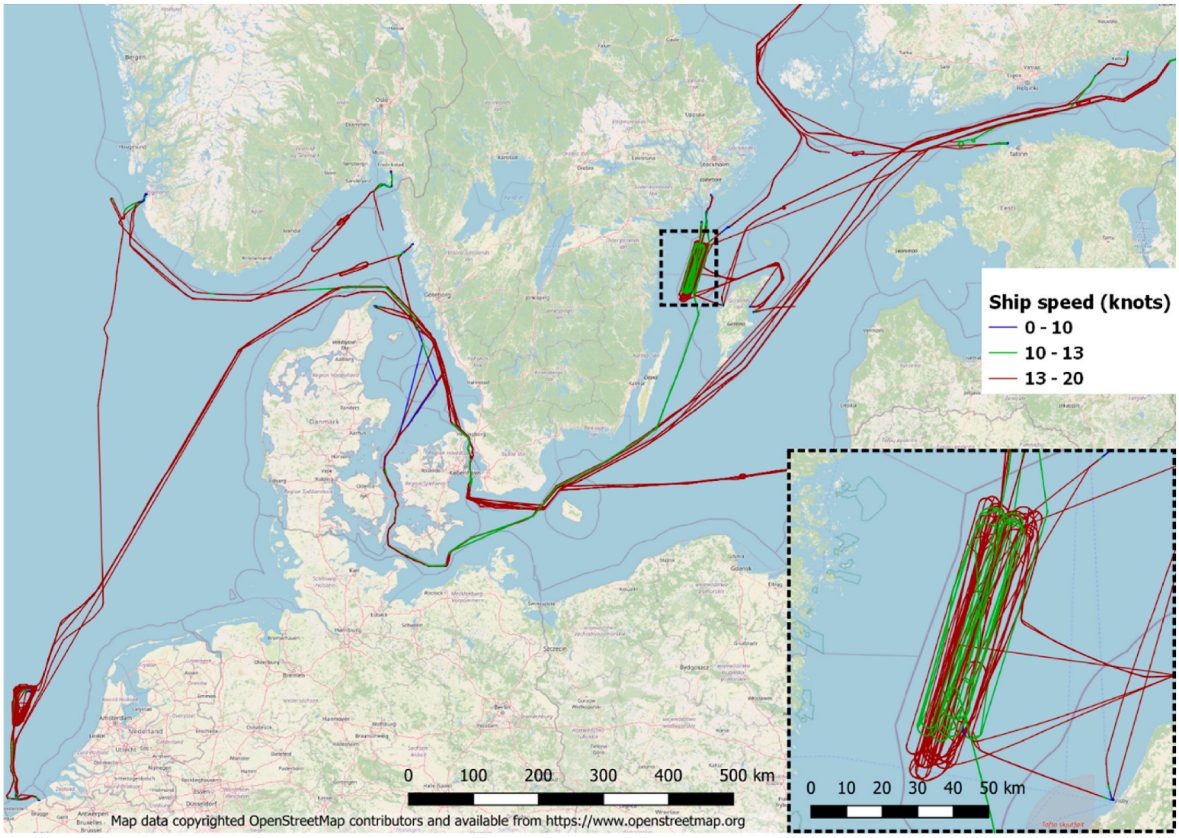

Fig. 4. Sailing paths of the LNG feeder between June 1st' 2022 and Aug 31st' 2022. The ship's speed over ground is illustrated with three different colors. The inset shows a zoomed in view of the sailing path of the LNG feeder in the area between the Swedish Island Gotland and Swedish coast during the same period which corresponds to 130 h spent on burning BOG. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

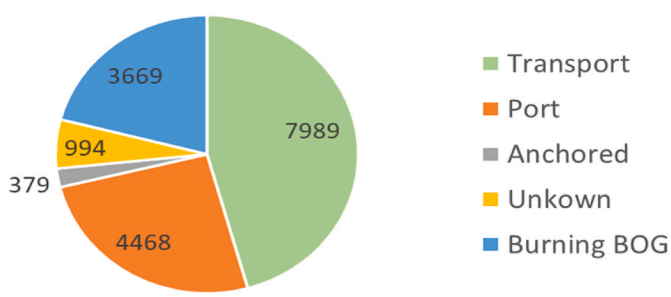

Fig. 5. Time (hours) that the LNG feeder vessel spent in the five different activity categories during the period Jan 1st' 2021–Dec 31st' 2022.

emissions for moving the cargo from port A to port B are divided with a much longer distance than required for the actual distance between the ports. On the other hand, if applying an approach using distance tables to calculate the CO_2 emissions for transport of cargo from port A to port B, the result will lead to underestimation of the total CO_2 emissions for the specific voyage if not considering the BOG activity. Therefore, it is essential that LCA of LNG specify and analyse the time LNG bunker vessels spend at sea burning BOG. Apparently, individual ships may spend up to 32% of their time sailing, burning boil off gas, implying both an increased navigational risk as the ship spend more time at sea, and unnecessary loads of e.g. nutrients and metals to the marine environment. Although the nutrient loads from individual ships are small compared to the annual nutrient loads to the Baltic Sea (Raudsepp et al., 2019), the potential resulting volumes of micro algae can be significant at local scales when the BOG activity is concentrated to a delimited area (Fig. 4). Further, shipping is recognized as one of the primary sources of copper input to the Baltic Sea (Ytreberg et al., 2022), and here we show that 169 kg copper per year is entering the marine environment, without being motivated by the need for transport. Copper is also a finite and rather expensive resource, (9.05 USD/kg, accessed Feb 23rd, 2023, Insider Inc, 2022).

This study highlights abnormal behaviour of LNG feeders, traveling in circles to burn their BOG, which has not been observed as a common activity pattern for large LNG tankers. However, during the relative low prices of LNG during the fall 2022, also large LNG tankers started to travel in circles to burn their BOG, awaiting more favourable prices for their cargo. One suggestion to enforce a change in behaviour and save environment could be to add a price on emission for ships. Regulating vessel activity in relation to the actual transport work is an interesting thought, but probably not practical feasible. However, as shown by Liu et al. (2019), shipping of waste was estimated to be responsible for 15% of the CO_2 emissions in the US-China bilateral trade. In 2017, the Chinese government banned the import of 24 types of solid wastes, which likely also has reduced associated CO_2 emissions.

An alternative to burning BOG at sea is to connect the ship to the existing gas grid. However, this option requires stationary land-based investments. Where to locate such facilities and how the business model for such facilities would look like is unclear and needs further investigations. Another alternative, to burning unnecessary BOG, could be installation of a regasification unit onboard this ship to transfer the BOG into LNG again. According to Yuan et al. (2019) there are several different options for this process and which option is best for LNG feeders needs to be further investigated.

To summarise, current economic incentives lead to unnecessary emission and risk of ship collisions. Large demand oscillations in the

European energy market will lead to a fluctuating LNG price and thereby a market to store LNG onboard ships. To change these market conditions there is a need to create economic initiatives that instead promote reduced emissions. Today there are at least three possible options for decision makers to consider: subsidise installation of regasification units, subsidise land-based infrastructure that could take care of the BOG or put taxes on shipping emission. The feasibility of these options should be investigated in future studies.

5. Conclusion

Due to economic incentives, LNG feeder vessels may spend a substantial share of their time at sea burning BOG, decoupled from actual transport work. In the present case study, 32 % of the vessel's time at sea was spent on burning BOG. To optimize economic profit on a variable gas market, there are potential incentives also for other types of vessels, such as large LNG tankers, to increase their time at sea burning BOG. It is essential that LCA of all type of LNG vessels consider the type of vessel activity when assessing the climate and environmental footprint of maritime transport. In sensitive areas, like the Baltic Sea, extensive measures are taken to reduce input of nutrients and hazardous substances (HELCOM, 2021). Preventing shipping activities that are not related to actual transport work, should be a low hanging fruit to reduce the environmental pressure. Future studies could include a larger number of ships and ship types, and economic valuation of the degradation of the environment. However, given the scientific consensus on the urgent need to reduce climate impact and improve the environmental status of our oceans, current knowledge should be enough to incentivize installation of reliquefication equipment onboard LNG vessels.

CRediT authorship contribution statement

Axel Hörteborn: Formal analysis, Writing. **Ida-Maja Hassellöv:** Environmental estimations, Writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.139461.

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