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Long-term energy efficiency improvement for LNG carriers

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Summary

With the booming natural gas trade, there has been huge growth in demand for liquefied natural gas (LNG) carriers, the primary transportation method for intercontinental trade of natural gas. This study offers a novel analysis that connects 2011 in-use LNG fleet characteristics, global satellite data on ship movement, and literature on LNG trade to assess the long-term prospects for increasing the energy efficiency of LNG carriers. This analysis also investigates how efficiency characteristics (age, size, technology, operational practices) influence the efficiency of the LNG fleet, and develops a ship stock turnover model to independently track technical and operational efficiency practices in LNG carriers. The findings indicate that industry-leading LNG carriers are about 40% more efficient than industry laggards. This analysis indicates that by fully embracing the available technical and in-use practices of the low-carbon industry leaders of today, the fleet could reduce CO_2 emissions by 20 million metric tons (MMT) by 2040, or about 8 MMT of natural gas, equivalent to $4 billion savings in the LNG supply chain. This study has important implications for the shipping industry and policymakers. The industry must address split incentives to take the advantage of energy-saving opportunities. And regulations that set targets for the energy efficiency of the in-use fleet may ultimately help the industry harvest the efficiency gains while mitigating its climate impact.

1. Introduction

Natural gas is receiving considerable attention as an alternative transportation fuel. It offers the inherent advantage of releasing less carbon per unit of energy than petroleum-based fuels. The fuel's recent supply boom, resulting from the development of new extraction techniques in the United States and elsewhere, has led to

a sustained period of low natural gas prices and spurred major investments in the infrastructure for its production, storage, and distribution. The growing demand for natural gas has led to a boom of intercontinental trade in LNG. According to the International Gas Union (IGU), global trade in 2013 reached 236.8 million metric tons (MMT), the third highest figure ever registered.[1]

East Asian nations are the biggest consumers of LNG. Lacking enough resources to feed their growing appetite for energy, the four major Asian economies—Japan, South Korea, China, and India—accounted for about 60% of world LNG imports in 2013.[2] Both Japan and South Korea rely heavily on natural gas to fuel their power sectors and their petrochemical and refinery industries. With an economy five times as large as South Korea's, Japan increased its reliance on LNG on the heels of the Fukushima nuclear disaster and generated 40% of its electricity from natural gas in 2012. LNG demand from India and China is growing even faster, albeit from lower bases. India's LNG imports surged by 700% between 2004 and 2012, while Chinese imports expanded from virtually zero in 2005 to 710 billion cubic feet in 2012, leading the country to surpass India as the world third largest importer (Figure 1). The staggering growth of both countries is being driven by rapid economic development. Furthermore, the sheer size of both economies and the relatively low contribution of natural gas to the generation mix in their electricity sectors foretell robust demand growth in the future. For example, with natural gas still generating only 2% of electricity in China and coal providing 60%, weaning the grid off coal in favor of natural gas has raised the prospect of heightened demand for LNG in the region.

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1   International Gas Union (2014). World LNG Report – 2014 Edition.
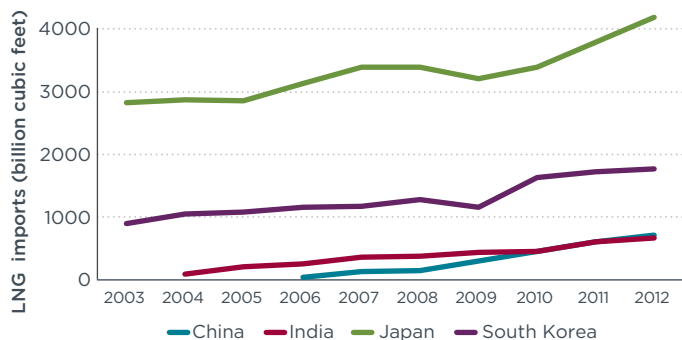2   Ibid.

Figure 1: LNG imports to Japan, South Korea, China, and India[3]

The robust demand for natural gas has widened the price gap between suppliers and consumers. The average cost of natural gas in East Asia is about $16 per million British thermal units (mBTU), compared with $11 per mBTU in Europe and $4 per mBTU in North America.[4] The price differentials between Asia and North America and, to a lesser extent, between Europe and North America and between Asia and Australia have raised prospects for more LNG trade.

These demand increases and strong price differentials have spurred explosive growth in the LNG carrier fleet. Between 2003 and 2012, LNG carrier capacity grew at a compound rate of 15% per year (Figure 2). Moreover, as the charter rate plunged in other shipping sectors, chartering a LNG carrier became more expensive, reaching a historic high figure of more than $12,000 per day in 2012. Although fleet growth leveled off in 2013 amid the uncertainty of LNG exports from the US and the delay of greenfield projects in Australia, the industry is likely to resume growth as new ships on the order book are scheduled to join the fleet in 2014 and 2015[5].
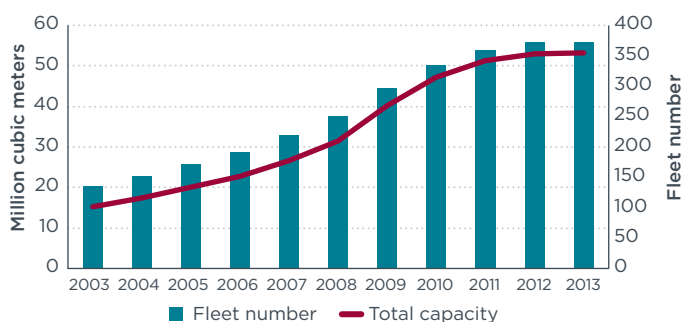

Figure 2: The capacity growth of LNG carriers

The long-term prospects for the industry are promising, buoyed by a number of economic and political factors.

First and foremost, the wide price spread between gas suppliers and consumers will continue to promote the expansion of the LNG fleet. Even at the long-term cost of $7.80 per mBTU, as the US Energy Information Administration (EIA) estimated in its latest Annual Energy Outlook,[6] the price in North America is still less than half that in East Asia and 60% of the price in Europe. The arbitrage opportunity will give rise to more inter-continental natural gas trade, creating robust demand for LNG carriers. Second, natural gas demand shows no sign of retreating, as major consumers in East Asia continue to use natural gas to reduce their reliance on coal and nuclear. Although countries such as China are believed to have vast reserves of natural gas, according to some estimates,[7] large-scale exploitation will require decades of effort. Imports will remain the most feasible way to meet domestic demand. Last but not least, the export bottleneck will diminish as greenfield projects in Australia finally begin to produce and the US Department of Energy (DOE) accelerates its review of LNG export terminals. Even before the natural gas boom was in full display, the International Maritime Organization (IMO) has forecasted a 150% increase in the number of LNG carriers between 2007 and 2020 and a 60% increase between 2020 and 2050, with the number of carriers larger than 200,000 cubic meters (CBM) increasing from just four in 2007 to nearly 300 in 2050.[8]

One of the major challenges facing a global LNG market is the lack of fungibility, a key measure of an international commodity such as oil. The cost of transporting crude oil through tankers, for example, is less than 3% of end use gasoline cost.[9] In comparison, transporting LNG accounts for 25% of the total fuel cost.[10] The charter rate, the daily rate of hiring a LNG carrier, accounts for about 45% of the transportation cost, followed closely by energy cost (40%) (see Figure 3).[11] While the charter rate tends to gravitate toward the long-term average of $80,000 per day, the costs of marine diesel fuels and natural gas that power LNG carriers are likely to escalate in the future. The global sulfur limit of marine diesel fuels is likely to drop to 0.5% by 2020 from 3.5% presently. The US Environmental Protection Agency (EPA) estimates that the switch from high-sulfur heavy fuel oil (HFO) to lower-sulfur marine diesel oil (MDO) would raise fuel costs by 40%.[12] In the Emission Control Areas (ECAs) that cover the 200

3   International Gas Union. World LNG Report, various editions.
4   Federal Energy Regulatory Commission (2013). World LNG Landed Price. Available at http://www.ferc.gov/market-oversight/mkt-gas/overview/ngas-ovr-lng-wld-pr-est.pdf.
5   Clarkson Intelligence (2013).
6   Energy Information Administration (2014). Annual Energy Outlook 2014.
7   Nakano, J et al. (2012). Prospects of share gas development in Asia. Center for Strategic and International Studies.
8   Buhaug et al. (2009). IMO 2nd GHG Report.
9   American Petroleum Institute (2010). Tankers Fueling American Life.
10 Jefferies (2013). LNG & LPG Shipping Fundamentals.
11 Timera Energy (2012). Getting to grips with LNG shipping costs.
12 Environmental Protection Agency (2009). Proposal to designate an emission control area for nitrogen oxides, sulfur oxides and particulate matters.

nautical miles (nm) from the coastline of North America, the Baltic Sea, the North Sea, and the English Channel, ships will be required to use marine gas oil (MGO) with 0.1% sulfur, resulting in even higher costs. Additionally, both EIA and IEA have projected higher natural gas prices over the next decade, meaning an increase in the cost of natural gas used as fuel.[13,14]
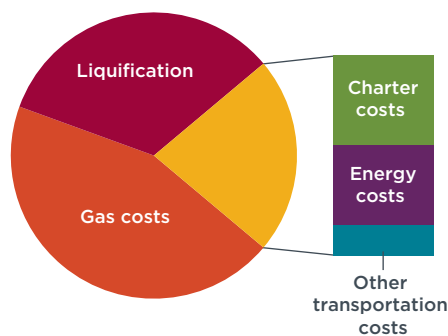
Figure 3: The cost of the LNG supply chain[15]

The IMO has adopted its Energy Efficiency Design Index (EEDI) to curtail energy consumption by establishing energy improvement target for newly built ocean-going vessels, including LNG carriers. The EEDI is projected to save the shipping industry $50 billion in energy costs by 2030.[16] However, as ships tend to have a lifetime of 30 years or more, the EEDI will not be able to shrink total energy consumption of any shipping sector. For this reason, the IMO is considering measures to improve the energy efficiency of the in-use fleet. This initiative, if it is finalized as regulation, could spur the industry to reduce energy consumption from its vast in-use fleet. Given the importance of energy cost in the LNG supply chain, in-use ship efficiency presents a particularly promising opportunity to align environmental benefits with the business bottom line for LNG carriers.

The purpose of this paper is to examine the energy consumption and CO_2 emissions of LNG carriers, and to evaluate key factors that influence their potential for energy savings. We first describe the state of LNG trade and the LNG carrier sector, then examine present and projected CO_2 emissions and energy consumption of LNG carriers between 2010 and 2040, and close by estimating potential energy savings through improved efficiency.

2. Data and assumptions

2.1 SHIP EFFICIENCY, FLEET TURNOVER MODEL, AND GHG EMISSIONS

Two measures of efficiency are characterized in this study. Technical efficiency (TE) is the efficiency of a ship in its as-designed condition (straight from the yard). TE is derived from the EEDI formula based on data from Clarkson Intelligence and Smith (2013). Operational efficiency (OE) is an estimate of real-world efficiency as characterized by the relationship between the transport demand (e.g., tonnes of a commodity shipped) with actual capacity-distance (e.g., tonnes cargo x nm sailed). The OE in this study is taken from normalized operational efficiency data from Smith (2013), which itself is estimated using the IMO average utilization rate and real-world ship speed data in 2011. Both TE and OE in this study are expressed in terms of gram CO_2/ton-nm.[17]

Additionally, we developed a global LNG carrier fleet turnover model to forecast operational efficiency trends between 2009 and 2050. The model is based on the IMO population forecast of LNG carriers between 2007 and 2050 and is used to project new ship entry, the shipping fleet population at large, overall efficiency, and GHG emissions. We backcasted the population of LNG carriers until 1982 using the energy consumption of the shipping industry as a primary input. Assuming a 25-year life span of LNG carriers, we projected the profile of the LNG fleet until 2050 and the average efficiency improvement of the industry, taking into consideration EEDI implementation in 2015. We then calculated total CO_2 emissions using the OE, ship population, and average transportation supply of each individual ship.

2.2 ENERGY CONSUMPTION OF LNG CARRIERS

About 350 LNG carriers operated in 2014.[18] They tend to be large ships powered by 25–40 megawatt engines and carry 120,000–180,000 CBM of LNG each.[19] These tankers can boil off a portion of the LNG cargo for propulsion, or they can use marine distillate or residual fuel, or use each in some combination of zero to 100%. In practice, LNG carriers need to consume boil-off gas (BOG) to keep the cargo cold, the amount of BOG being a function of the heat leak into

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13 International Energy Agency (2011). World Energy Outlook 2012.

14 Energy Information Administration (2014). Annual Energy Outlook 2014.

15 Timera Energy (2013). Getting to grips with LNG shipping costs.

16 ICCT (2011). The Energy Efficiency Design Index for New Ships.

17 It should be noted that there are other ways to express energy efficiency, among them energy/ton-nm, that may be more standard than gram CO_2/ton-nm. However, other literature such as IMO GHG reports have been using CO_2/ton-nm as a proxy for energy efficiency, a practice that we follow in this paper.

18 International Gas Union (2014). World LNG Report – 2014 Edition.

19 Ibid.

the tank, which itself is determined by the insulation of the tank. LNG carriers are usually designed so that the amount of BOG is equivalent to the amount of energy required at the design speed, in which the vessel will burn 100% BOG. Operationally other factors influence the actual BOG, such as ambient temperature and the temperature of the LNG when loaded. Immediately after loading there may not be enough gas as the cargo is cold, so the vessel will start slow and speed up as the BOG increases. LNG can also be intentionally vaporized to provide more gas, or diesel fuels could be used to supplement the fuel requirements.

The Qatar series of ships (Q-flex, Q-max) was designed at a time when the price of heavy fuel oil (HFO) was historically low. They are the only LNG ships that were not designed to burn LNG for propulsion, instead using HFO to reliquefy the BOG. About 13% of LNG carriers are Qatar series.

Because of the flexibility of LNG carriers in using different types of fuels, prior studies that quantify energy consumptions from shipping did not examine the energy mix in LNG carriers. Buhaug et al. (2009), for example, assumed all LNG carriers to use HFO, while Smith et al. (2013) calculated CO_2 emissions from LNG carriers based on natural gas as the only fuel. Given the fact that LNG carriers need to consume BOG for most but not all of their trips, this study assumes an energy mix of 80/20 between natural gas and marine diesel fuel, respectively.

2.3 GLOBAL SATELLITE DATA ON LNG CARRIER MOVEMENT

This analysis extends the work of Smith et al. (2013), which applied a novel use of Automatic Identification System (AIS) data to evaluate ship efficiency for long-haul transit. AIS is an automatic system through which location information is transmitted and exchanged via receiving stations and satellites for the primary purpose of avoiding collisions and facilitating recues. More recently, because of the detailed information they can provide on ship operation, shore-based AIS and satellite-based (S-AIS) data have increasingly been used to observe ship activities for the purpose of estimating energy consumption and emissions.[20] Observations of activities in the open ocean, based on positional reports from ships, offered an innovative way of quantifying shipping emissions and energy consumption. Operational practices, especially speed, can be estimated from S-AIS data to help estimate ship energy consumption and emissions. Based on Smith et al. (2013), Wang and Lutsey (2013) investigated how ship characteristics influence the in-use efficiency of the shipping fleet and assessed the long-term prospects for increasing efficiency of the shipping industry.

This research connects Smith et al. (2013)[21] and Wang and Lutsey (2013)[22] with LNG trading data, and looks specifically at the efficiency improvement potential of LNG carriers. S-AIS, with its worldwide coverage, makes a comprehensive analysis possible for the global LNG carrier fleet.
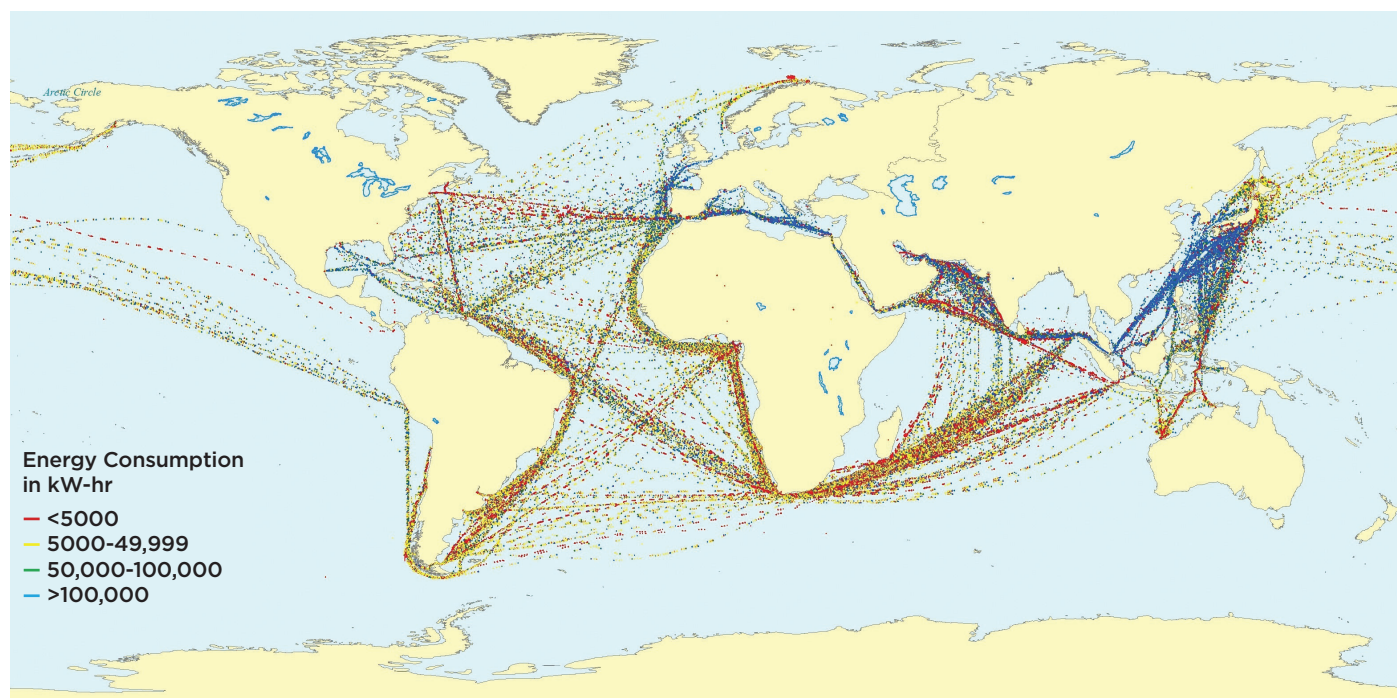
Figure 4: Energy consumption of LNG carriers in 2011

20 Jalkanen, J et al. (2013). A Comprehensive Inventory of the Ship Traffic Exhaust Emissions in the Baltic Sea from 2006 to 2009. AMBIO.

21 Smith et al. (2013). Assessment of shipping's efficiency using satellite AIS data.

22 ICCT (2013). Long-term potential for increased shipping efficiency.

3. Findings

This section summarizes key findings from this research, including the present-day operational efficiency of LNG carriers across different ship sizes with varying operational speed and design efficiency. The application of operational and technical practices is integrated with the fleet turnover model to project fleet-wide CO_2 emissions, energy consumption and savings, and methane slip over the next several decades.

3.1 THE PRESENT-DAY OPERATIONAL EFFICIENCY OF LNG CARRIERS

Figure 4 demonstrated the energy consumption of LNG carriers around the world in 2011. It illustrates major shipping routes of LNG trade. As expected, shipping lanes around East Asia, Western Europe, and Middle East have the highest energy consumption, signifying the LNG trade activity there.

Figure 5 shows that LNG carriers exhibited vastly different operational efficiency. Our analysis estimates that the average operational efficiency of LNG carriers in 2011 was about 20 gram CO_2/ton-nm. Operational efficiency varies widely by ship, from as low as 12 grams CO_2/ton-nm to more than 25 grams CO_2/ton-nm. The top 5% most efficient LNG carriers emitted less than 12 gram CO_2/ton-nm, or 37% more efficient than the industry average. The 5% least efficient ones emitted more than 30 gram CO_2/ton-nm, or 47% less efficient than the industry average.
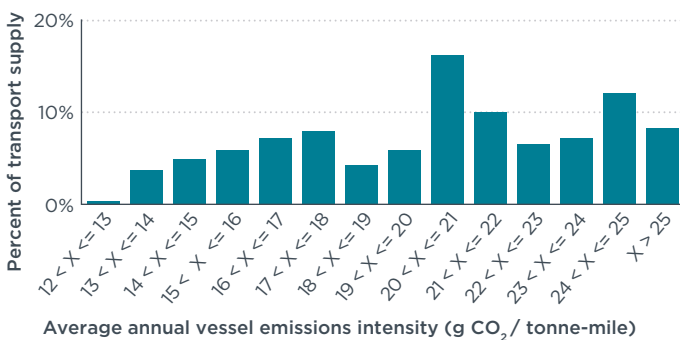
Figure 5: The average energy efficiency of LNG carriers

Table 1 summarizes the results of a regression analysis that examines how ship speed, age, and technical efficiency influence operational efficiency. The original regression model also includes the size of LNG carriers, but since technical efficiency is highly correlated with size, the latter was removed from the regression analysis to avoid multicollinearity. Robust standard error was used to calculate t values, as the original model also indicates conditional heteroskedasticity. With a sample size of 314, the model has a R^2 of 0.99. We add the caveat,

however, that the high R^2 does not mean the operational intensity is solely determined by speed, age, and how ships are designed. Rather, operational efficiency is calculated based on these factors in Smith et al. (2013). From another perspective, the high R^2 does show that the model is correctly specified.

Table 1 illustrates a positive relationship between the operational intensity with the designed intensity, speed, and age. The model forecasts that if the design efficiency increases by 1 gram CO_2 per ton-mile, the operational efficiency will increase by 1.9 gram per ton-mile, or about a factor of two. Similarly, a 1% speed increase will lead to an 0.26 gram CO_2/ton-mile increase in ships' operational intensity. By comparison, the influence of ship age on operational intensity is less significant. Older ships do have higher CO_2 intensity, but each additional year of a ship's age added only 0.1 gram CO_2/ton-mile difference operationally, and the relationship is only significant at a 10% level, while design intensity and speed are significant even at a 1% level.

Table 1: Regression analysis results

| Y: Operational intensity (CO_2 gram/ton-mile)	Coefficient	Robust Std. Err.	t	P>|t|
Interception	-22.75	1.73	-13.15	0.00
X_1: Technical intensity (CO_2 gram/ton-mile)	1.91	0.51	37.13	0.00
X_2: Speed (operational speed/designed speed)	26.90	2.00	13.46	0.00
X_3: Vessel age	0.15	0.09	1.70	0.09

3.2 PROJECTIONS

The efficiency practices discussed above have important implications for long-term fleet-wide energy consumption and CO_2 emissions from LNG carriers. In addition to a "frozen technology" scenario without the EEDI, a baseline EEDI scenario and an incremental CO_2 emission reduction scenario were developed. The incremental CO_2 reduction scenario assumes that LNG carriers on average will, by 2030, reach the operational efficiency level achieved by the top 5% LNG carriers as of 2011 using technology and operational best practices.

These scenarios, when combined with shipping activity growth projections through 2050 in the fleet turnover model, illustrate very different CO_2 emission outcomes. As shown in Figure 6, under the top 5% in-use efficiency leaders scenario, the LNG sector's emissions in 2040 will be about 20% below the level with only the current

EEDI standards in place. This analysis suggests that the magnitude of potential CO_2 emission reduction from additional in-use efficiency measures is comparable to the expected reductions from the in-place EEDI standards between now and 2040.

Figure 6 also implies that total CO_2 emissions from LNG carriers will not stabilize or reverse even if the top 5% efficiency practices in 2011 are adopted widely. This contrasts with the shipping industry as a whole, where following the top 5% efficiency leaders would be projected to stabilize total CO_2 emissions, due to the high anticipated growth rate of the LNG trade that outpaces the possible efficiency gains. Without any measures taken, CO_2 emissions from LNG carries are likely to grow by 280% between 2007 and 2040. With EEDI in place, the growth rate will increase by 200% along the same period. A further efficiency improvement of the in-use fleet would lower the growth rate to 130% between 2007 and 2040.
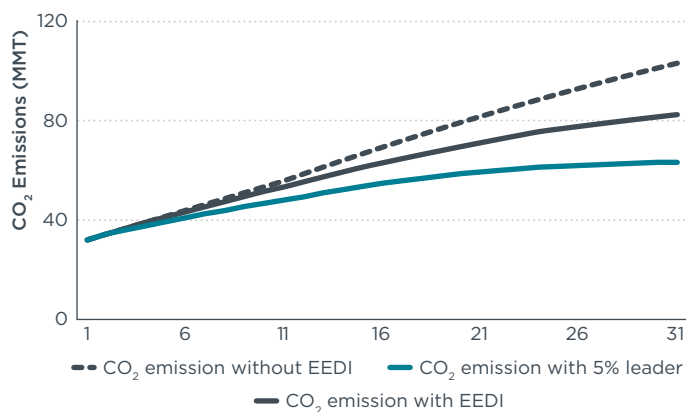
Figure 6: Projected global CO_2 emissions from LNG carriers, 2010 to 2040

This CO_2 reduction would be accompanied by a significant reduction of natural gas consumption. The total natural gas consumed by ships will be reduced by 8 MMT by 2040, equivalent to building two Sabine Pass LNG export terminal in the United States. The energy reduction presents an annual $4 billion savings in the LNG supply chain based on EIA's natural gas price projection.

4. Conclusions and future work

This research examined the energy efficiency of LNG carriers in 2011 and the energy and climate implications of international LNG trade, considering how efficiency characteristics such as age, size, technology, and operational practices influence the efficiency of the LNG fleet.

LNG carriers are one of the primary ways to move natural gas between continents. Our finding illustrates that if the

majority of the fleet follows the best practices performed by a few industry leaders, the fleet will continue to reduce its carbon intensity, reducing total CO_2 emissions by 20 MMT by 2040, or about 8 MMT of natural gas, equivalent to $4 billion savings in the supply chain. This represents a significant business opportunity to save natural gas from carriers for end use.

Although there are significant opportunities for LNG carriers to improve their energy efficiency and reduce operational costs, some barriers limit the effect and scale of realizing such opportunities. The single most important barrier is split incentives between shipowners and charterers attributable to fuel costs. Split incentives refers to a situation in which the actors that would benefit from energy efficiency measures are not the people paying for them, inhibiting the adoption of those measures (Jaff et al, 1994).[23] In the shipping industry, split incentives occur when there is a disconnect between the vessel owner, who controls capital spending and energy conservation efforts, and the operator, who is responsible for fuel cost (CE Delft, 2009).[24] Ships are typically chartered in one of four ways: spot or voyage charter, term or time charter, bare boat charter, or contract of affreightment (COAs). Under the spot/voyage charter, the shipowners agree to move a specific cargo on a specific ship from port A to port B. The shipowners are responsible for costs, including the fuel costs. Under the term/time charter, the shipowners provide a specific fully manned vessel to the charterer for a fixed amount of time. The shipowners pay the vessel costs and the charterers pay the voyage costs (fuel, port, and canal costs). Under the bare boat charters, the shipowners provide a specific ship without crew to charterers. The charterers are responsible for vessel and voyage costs (except for capital costs). Under the COAs, the shipowners agree to move a specific amount of cargo over a specific time from port A to port B without specifying the ship. Shipowners pay vessel and voyage costs.

Most LNG carriers are under term or time charters. The long-term charterer guarantees shipowners stable cash flows during a relatively long period of time while insulating charterers from a volatile market and ensuring them enough capacity for the gas supply. However, such an arrangement also gives rise to split incentives that discourage shipowners from investing in fuel-efficient technologies. One may expect that more energy-efficient ships could theoretically have higher charter rates in the market. In practice, this is rare because of the diversity of the charter market and the difficulty "guaranteeing" improved fuel consumption on a LNG carrier whose

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23 Jaffe, A., and R. Stavins (1994). The energy-efficiency gap: what does it mean? Energy Policy 22 (10): 804–810.

24 CE Delft (2009). Technical support for European action to reducing greenhouse gas emissions from international maritime transport.

speed is heavily affected by weather and other unpredictable sea conditions.

A limited number of LNG carriers are hired under the spot market in the hope of reaping the benefit of the market upswing. Even under the spot charter, the current system requires that shipowners be responsible if the vessel arrives outside of the originally designated discharge window. If vessels sail at normal speeds to the discharge port and arrive within the designated window but the terminal is not ready to discharge the cargo, the time counts as "laytime" and once the specified allowed laytime is exceeded, charterers must pay shipowners "demurrage" at a rate (typically US dollars per day or a fraction thereof) specified in the charter. The opportunity to save fuel by sailing slower and arriving when the berth is ready for the vessel is lost in the current system.

The current LNG market condition makes energy efficiency less appealing as well. With charter rates at a record high, charterers are looking for less expensive ships regardless their efficiencies. The growing price gap between gas suppliers and customers also lead charterers to care less about the efficiency as long as a stable charterer rate is secured. What is more, encouraged by the higher charter rate, shipowners are less inclined to market their ships as more efficient as opposed to more affordable.

In addition to split incentives and the current market condition, other factors also influence shipowners' and charterers' decision to improve ship efficiency, including the industry's short (usually two to three years) investment horizons, shipowners' inability to charge an efficiency premium in the secondhand market, and shipowners' difficulty in persuading banks to finance retrofit technologies under current financial situations. These factors mask market signals that would otherwise promote LNG carrier energy efficiency.

The primary approach to rectifying market failures is through regulations, including mandatory energy efficiency targets. This study shows that operational efficiency improvements for LNG carriers could provide substantial climate and economic benefits, mitigating the industry's climate impact while improving its bottom line.

Public policies should also take into account the climate impact of methane leakage from LNG carriers. Several recent studies have highlighted the importance of methane leakage when natural gas is used as a transportation fuel. A recent ICCT study (2013) found that lifecycle methane leakage reduces the GHG reduction benefit of LNG relative to marine diesel fuel by more than a half.[25] In some cases, methane leakage leads to increased total

GHG emissions from LNG use in marine applications. Tank-to-propeller emissions alone, according to Rolls-Royce methane emissions from new EPA-certified natural gas marine engines, are 4 grams per kilowatt-hour (g/kWh) of engine output (based on Trent 2012; Horgen 2012).[26,27] This equates to less than 2% of fuel consumption, but after converting to CO_2-equivalent (CO_2-e) emissions using a 100-year global warming potential (GWP) of 25, the CO_2-e from methane leakage is equivalent to about 15% of an LNG carrier's CO_2 emissions, or about 5 MMT of CO_2-e in 2007.[28] It is not clear how technical and operational efficiency improvements in LNG carriers will affect future leakage rates, if at all. In addition, further information about the use, reliquefaction, and possible venting of BOG is also needed to inform policies to control GHG emissions from LNG carriers.

25 ICCT (2013). Assessment of fuel-cycle impact of LNG in international shipping.

26 Trent, B. (2012). Gas Propulsion System for Tugs. Rolls-Royce.

27 Howarth, R. W., Santoro, R., and Ingraffea, A. (2011). Methane and the Greenhouse-Gas Footprint of Natural Gas from Shale Formations. *Climatic Change* 106 (4): 679–90. doi:10.1007/s10584-011-0061-5.

28 Assuming 220 g/kWh of specific fuel oil consumption, and 2.75 CO_2 per gram of emission factor.