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US liquefied natural gas (LNG) exports: Boom or bust for the global climate?

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ABSTRACT

Due to surging natural gas production, the United States is now a growing exporter of liquefied natural gas (LNG) to overseas destinations. However, the potential greenhouse gas implications from increased US natural gas remain unclear. Through a hybrid lifecycle energy strategy analysis, we investigate potential greenhouse gas scenarios of US LNG exports to Asia, the largest source of global LNG demand. We find that the climate impacts of US exports to China, Japan, India, and South Korea could vary tremendously. Annual global lifecycle emissions range from −32 to +63 million metric tons CO_2e per billion cubic feet (Bcf) per day of exports. Despite this range, emissions are not likely to decrease and may increase significantly due to greater global energy consumption, higher emissions in the US, and methane leakage. However, international climate obligations are a critical uncertainty underlying all emissions estimates. Our results indicate the need for further research into quantifying the climate impacts of LNG exports, and energy exports more generally.

1. Introduction

Natural gas production in the United States has increased significantly in the last decade due to the shale revolution [1]. Originally faced with the prospect of having to import massive amounts of liquefied natural gas, the US is now becoming a large net exporter. Dry natural gas production increased by more than 35% since 2006 and is projected to grow further through 2020 [2]. Natural gas prices have fallen significantly, with major economic and emissions benefits domestically [3].

The shale revolution is now on the verge of rippling across the world. Rapidly increasing domestic natural gas production in the United States is leading to mounting pressure from industry and legislators to export domestic natural gas to other countries. The Department of Energy (DOE) has received applications for projects with a cumulative natural gas export capacity of more than 40 Bcf/day for permission to construct facilities to liquefy natural gas for export to countries without Free Trade agreements [4]. Exports from the first of these terminals recently began, with more under construction or under regulatory consideration.

Recently, many studies investigated the environmental implications of the domestic natural gas boom in the US, which has largely replaced coal for electricity generation. Natural gas is methane, which is itself a powerful greenhouse gas. Natural gas can leak out of its infrastructure and into the atmosphere during normal production and transportation operations, leading to greenhouse gas emissions greater than combusting the natural gas. Accordingly, despite having lower combustion emissions than coal, Howarth argued that leakage of natural gas undermined the lifecycle greenhouse gas advantages of natural gas [5]. Subsequent research found that while methane leakage may be higher than official inventories, natural gas remains better than coal for electricity generation for domestic uses [6–9]. This is due to the relative efficiency of the US natural gas fleet, relative inefficiency of the coal fleet, coal mine leakage, and because natural gas has replaced primarily coal instead of other fuel sources [9].

However, relatively few studies have examined the global greenhouse gas implications of expanded US LNG exports. To date, the DOE and the Federal Energy Regulation Commission (FERC), the federal agencies responsible for approving LNG export projects, have not comprehensively examined the impacts of export approvals on global greenhouse gas emissions. The only study conducted by DOE thus far was limited to examining the replacement

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of coal with natural gas for electricity generation, had key methodological shortcomings, and did not account for several aggravating factors [10].

A similar study by Abrahams et al. was more comprehensive, including a first order consequential lifecycle analysis, which is better able to capture replacement effects. Nevertheless, this study also only examined, natural gas replacing coal, did not fully examine domestic and international markets impacts, and did not analyze how energy strategies of importing countries could affect emissions from LNG [11].

This lack of inquiry into emissions and LNG is unfortunate, as the energy and carbon intensity of its conversion could be significant. The liquefaction and transportation processes are very energy intensive, as are the end uses (and displaced uses) of exported LNG.

Critically, the emissions impacts of expanded LNG exports can be difficult to determine because they impact activities in two or more country's energy markets: the exporter and the importer. Accordingly, analyses that look narrowly at only one replacement scenario (i.e. coal to LNG) are incomplete looks of global market effects.

This study more accurately and comprehensively assesses the greenhouse gas emissions of US LNG exports by developing a bounded hybrid lifecycle – energy strategy analysis. This new approach combines lifecycle emissions uniquely normalized to an export metric with an analysis of domestic and international energy markets. By investigating four of the largest LNG importers in 2013 (China, Japan, India, and South Korea), we identify eleven potential uses of US LNG in Asia, the most likely destination. Through developing individual lifecycle emissions for these uses, we bound potential changes in greenhouse gas emissions per 1 Bcf/day of exports. Further, this study measures how methane leakage, export-driven changes in domestic emissions, and energy demand growth affect global greenhouse gas emissions from exports. Integrating analysis of key energy concerns in each country with lifecycle profiles of individual technologies more fully captures the dynamics at play in international fuel switching scenarios.

2. Identifying the potential uses of exported LNG in Asian countries

The countries that are likely to import LNG from the United States face energy challenges that are somewhat distinct from those in the United States and Europe. The nuclear accidents at Fukushima generally soured public opinion on nuclear power in Asia, leading to calls to permanently close existing nuclear reactors and stop construction of new ones [12–15]. As such, heavy dependence on imported fossil fuels in Japan and South Korea create significant energy security concerns. In China and India, efforts to fight worsening air pollution conflict with ever rising demand for energy [15].

With diverse and complex energy dilemmas facing each country, the potential emissions associated with each additional Bcf/day of US LNG exports could vary considerably. They would depend on many factors, including: destination country, global markets, energy growth, energy security issues, fuel choices, and environmental concerns. Examining the energy challenges and strategies of importing countries is critical to fully assessing the potential lifecycle emissions of US LNG exports. Highlights of a quantitative and qualitative country-by-country analysis are presented in Fig. 1, with detailed analysis following in the rest of this section.

As the first and second largest respective importers of LNG globally, Japan and South Korea face two major challenges regarding their future LNG demand: near complete dependence on fossil fuel imports to meet energy demand and a diminished role for nuclear energy following Fukushima [17,18].

As advanced, developed economies, both countries have high energy and electricity demand. Japan, a series of islands, and South Korea, an isolated peninsula, have limited fossil fuel reserves and rely on large amounts of imports to meet domestic energy needs [19,20]. Beyond LNG, both countries are among the largest importers of coal in the world. This heavy dependence has created stark and distinct energy security concerns due to volatility in global fossil fuel markets. With limited fossil fuel production, Japan and South Korea originally turned to nuclear power to diversify energy sources and reduce import dependency [21].

The three-reactor nuclear meltdown at the Fukushima Daichi power station fundamentally altered the energy outlook for both countries. The effects were most immediate in Japan, which shut down its 48 nuclear reactors in the immediate aftermath of the accident [17]. Large increases in fossil imports, particularly LNG and fuel oil, were initially used to bridge the consequent energy gap. More recently, Japan has turned to coal to meet energy demand. With lost nuclear output replaced by fossil fuels, Japan revised a targeted 25% reduction in greenhouse gas emissions to only a 3.8% reduction, citing lost nuclear power as the main cause [22]. Japan's heavy reliance on imported LNG makes coal an attractive energy source as it provides fuel import diversity, limiting the ability of US LNG to replace Japanese coal consumption.

The nuclear industry was similarly hard hit in South Korea, which relied on nuclear power for 29% of its electricity in 2012 [18]. Following the discovery of falsified certificates for components at existing plants in 2012, four reactors were shut down temporarily. Driven by public safety concerns, nuclear energy's planned role decreased greatly in a recent proposed long-term energy plan. As in Japan, concerns about overreliance on LNG may limit the ability of US LNG to displace coal in South Korea.

The energy situation in South Korea and Japan is further complicated by the recent international agreement to limit carbon emissions in Paris. As part of this agreement, South Korea has pledged to reduce its economy-wide emissions 37% below business-*as*-usual forecasts by 2030 [23]. Similarly, Japan pledged to reduce its emissions 26% below 2013 levels by 2030 [24]. It is unclear whether either country will be able to meet this pledges on this current trajectory. As informed by our analysis below, importing U.S. LNG will not necessarily reduce emissions in either country. It depends on what the LNG is replacing and what second order international market effects are.

China's growing importance as an energy consumer cannot be understated, and at least three pressing challenges relate to its demand for imported LNG: dramatic increases in economic growth and energy consumption, growing dependence on foreign imports, and severe air pollution resulting from heavy use of coal.

Between 1990 and 2010 China's economy grew almost fivefold, and its energy use more than doubled, partially explaining why it now leads the world in total emissions of greenhouse gases. [25] Today, China is the world's largest coal consumer and the second largest oil consumer [26]. Responsible for almost half of global coal consumption, 69% of Chinese primary energy consumption in 2011 came from coal, which dominates the power and industrial sectors. The usage of natural gas is also growing in China, especially within the residential sector, and it now represents 3% of China's total primary energy supply. Due to its expanding economy, China has witnessed unprecedented growth in the demand for energy, led by the manufacturing sector and followed by the residential sector [27,28].

This massive energy growth has led to increasing levels of fossil imports. In 1993, energy imports emerged as a major concern to Chinese planners as net imports of oil ended “three decades of self-sufficiency.” [29] By 2009, soaring demand made China a net coal importer; internal infrastructure constraints led to increasing

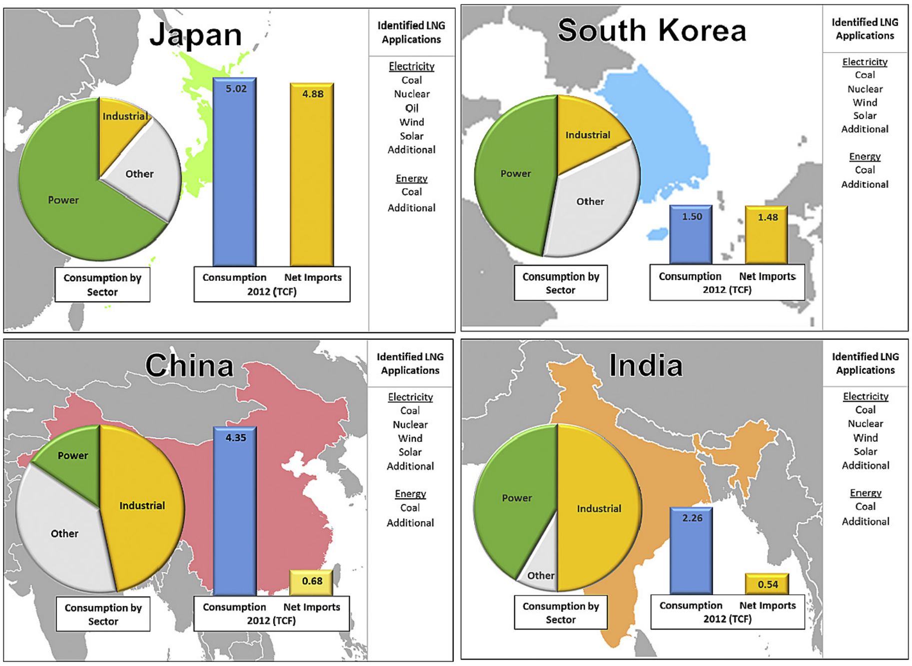


Fig. 1. Natural gas consumption, imports, and identified LNG applications by country.
Source: Natural Gas Statistics – [16]. Identified LNG Applications – this study. Note: Other refers to Commercial, Residential, and Transportation Sectors.

seaborne deliveries [26]. Despite investments in unconventional sources of gas, such as coal-bed methane and shale gas, Chinese demand for natural gas already requires large and quickly growing levels of imports [30]. China is building many LNG terminals to facilitate imports of LNG, along with a pipeline from Turkmenistan and a recently signed gas deal with Russia.

Finally, heavy utilization of coal has led to the most severe and pressing air pollution issues in the world, with deteriorating air quality in many Chinese cities. This severe air pollution brings significant impacts on health and mortality to Chinese cities [31]. Natural gas, which burns much cleaner than coal, could allow China to reduce its coal dependency and mitigate air pollution in major cities. However, China's ambitious domestic shale goals are facing technology and infrastructure constraints.

Although US LNG could be used to meet rising gas demand, it is likely that China will continue its strategy of diversifying its international natural gas sources, limiting the portion of US LNG that would flow to China [32]. It is unclear whether natural gas imports would displace existing coal consumption or would just be used to meet rising energy demand. Further, pressing air quality issues make replacing industrial or residential coal consumption more urgent, as the power sector can utilize scrubbing technologies.

China's air pollution challenges are further intensified by its recent international pledge at the Paris climate conference. China pledged to peak its carbon dioxide emissions by 2030 (at the latest), decrease CO2 GDP intensity by 60–65% from 2005 levels, and to increase non-fossil fuel energy consumption to 20% of total energy [33]. The role that LNG could play in these activities could be limited. In particular, U.S. LNG imports are likely to go to reducing industrial coal consumption as opposed to electricity. From an air pollution perspective this makes sense – as pollution control technologies can be applied to electricity generators, LNG is a top choice for reducing air pollutants from industrial emissions. As described below, however, there are notable carbon tradeoffs that would limit CO2 reductions from replacing industrial coal.

With the world's second largest population, a growing economy, and pressing energy needs, India faces very similar energy challenges to China: staggering increases in projected demand, burgeoning dependence on imported energy, and severe infrastructure constraints.

India's growing economy and population are dramatically increasing demand for energy. With an installed capacity of 189,000 MW in 2010, India already consumes the fifth largest amount of electricity in the world. Coal-fired thermoelectric power plants produced about 71% of the country's electricity in 2011–2012, with nuclear, hydropower, diesel and natural gas making up the remainder [34]. India is both the third largest consumer and producer of coal in the world. However, India's electricity sector relies on low quality coal, rendering coal-fired electricity generation inefficient and necessitating the import of metallurgical coal. Energy demand, for coal, natural gas, and oil is projected to continue to grow rapidly in coming years.

As in China, escalating energy demand is worsening the need for imports, which already supply about one-third of India's energy consumption. The country imports its three major sources of energy – coal, oil and natural gas, albeit in varying degrees. The IEA projects that by 2030, 91% of India's oil will be imported [35].

Soaring demand and rising imports underlie India's most pressing energy challenge: severe, persistent infrastructure constraints. The pace of infrastructure build out, including power lines, coal transportation capability, and generation capacity, has not kept up with demand. According to the Government's economic survey, the gap in supply and demand of electricity was roughly 9% from 2007 to 2012. Despite adding 55,000 MW of new generation capacity the gap was expected to remain unchanged for the fiscal year beginning in April 2012, with nearly 92,000 GW h (GWh) of demand going unmet [36]. In July 2012, this daunting shortfall for energy was partially responsible for the largest blackout in human history, when 680 million people lost power on two days [37]. Rolling blackouts continue to this day. India is thus looking for LNG and other energy sources to fill the energy supply and infrastructure gap in virtually any way possible.

More so than any other country in our analysis, US LNG exports to India are likely to serve additional energy demand and are very unlikely to displace coal use. This is especially true in light of India's pledge at the Paris climate conference: to install 175 GW of renewable capacity by 2020, reduce CO2 GDP emissions intensity 33–35% below 2005 levels by 2030, and increase non-fossil fuel share of power capacity to 40% by 2030 [38]. None of these pledges are absolute: as they are relative, they open the door for significant increases in overall energy demand even as CO2 intensity decreases.

3. Methods

3.1. Normalizing emissions and selecting end-uses

Two central tenants underlie the technology portion of our hybrid lifecycle – energy strategy analysis: emissions normalization and the breadth of technologies examined.

First, normalization is necessary because the cumulative global climate impact of US LNG exports will depend on the magnitude of exports and how LNG is used. However, decision making for LNG exports is currently made on a project-by-project basis. This paper normalizes the potential positive or negative lifecycle emissions from each potential use of exported LNG into a commonly used industry and government metric, Bcf/day. By normalizing emissions impacts into a 1 Bcf/day metric, the climate impacts from individual export projects can be analyzed. Importantly, this normalization also allows a comparison between different uses of natural gas, critical when examining emissions outside of the United States. Normal metrics for electricity emissions, such as kg/MWh, and industry emissions, such as emissions/heat output, can be readily converted into the Bcf/day metric.

Second, the examination of multiple applications and technologies is necessary because natural gas is a versatile fuel and can be used for electricity, heating, transportation, or as an industrial feedstock. In assessing lifecycle impacts from US exports, many existing government and industry analyses assume that liquefied natural gas will replace coal for electric generation. This represents the dominant paradigm in the United States, where coal is used almost exclusively for electricity and where increased natural gas production frequently offsets coal for electricity generation. However, this paradigm is not dominant in most of the countries that would use US LNG exports. A complete analysis of the lifecycle emissions of LNG needs to address all potential uses, of which this study examines eleven.

3.2. Justification for leakage scenarios

The three leakage scenarios developed in this study, 1.45%, 2.93%, and 5.87%, are based on data from EPA and Brandt et al. [6]. The 1.45% leakage rate is based on EPA's greenhouse gas inventory, with distribution emissions removed. The 2.93% and 5.87% leakage cases are based on worst case leakage scenarios from Brandt et al., similarly modified to remove a representative proportion for distribution [6]. These leakage scenarios are applied to international LNG cases as well as the domestic coal to gas fuel switching case. As such, the greenhouse gas benefits of replacing domestic coal in each scenario compared to international consumption are likely higher than indicated in the main body of the study. International applications would likely have some leakage between the regasification and consumption processes. This would lower the breakeven additionality rate for LNG applications and increase the emissions benefits of using gas domestically to replace coal.

3.3. Lifecycle emissions profiles of likely LNG uses

The identified uses of LNG in Asia range widely, covering applications in the electricity, industrial, commercial, and residential sectors. Accordingly, the greenhouse gas emissions of different uses have wide ranges. In order to understand the climate impacts of US exports, emissions profiles must be developed for each potential application. Lifecycle analysis (LCA) is a widely used tool to assess the complete environmental impacts of certain activities. By looking at the upstream and downstream environmental impacts associated with an activity, LCA provides the best methodology to identify the full climate ramifications of specific applications of LNG exports.

Country-specific lifecycle emission factors are often overlooked when examining lifecycle impacts of switching from coal to gas. For example, DOE's report on the lifecycle emissions of replacing Chinese coal with LNG is misleading as it uses the emissions profile of an American coal plant [10]. Chinese coal plants were built recently, resulting in greater efficiency and less emissions during combustion. To accurately compare the emissions of cross border uses of LNG, lifecycle profiles for coal generation in each importing country are needed.

This study combines data from multiple studies to create emissions profiles for eight types of electricity generation, of which five are country specific: Chinese coal, Indian coal, Japanese coal, South Korean coal, Japanese oil, nuclear, wind, and solar (see Table 1. Fossil emissions are based on three upstream processes (energy used for extraction, methane leakage, and transportation) and one downstream process (combustion). Emissions from the three non-fossil electricity technologies include different processes, including cultivation, fabrication, construction, operation, and decommissioning.

Compared to the United States and Europe, there are considerably fewer LCA studies examining domestic energy consumption in the countries profiled in this study. While the authors were able to determine lifecycle emissions for each identified use in CO2

Table 1
Lifecycle emissions factors for different technologies for LNG.

LNG Application	Location	KG CO2e Emissions/MWh	Source
Coal Generation	United States	1,050	This study
	China	894	S.Yu et.al.
	India	1,129	Agrawal et. al.
	South Korea	1,001	K.M. Lee et. al.
	Japan	1,005	H.Hondo
Oil Generation	Japan	740	H.Hondo
Coal (heating)	Global	107[a]	Composite
Nuclear	Global	66	Sovacool
Solar	Global	50	Nugent and Sovacool
Wind	Global	34	Nugent and Sovacool

[39–46].

[a] Coal for heating is in KGs CO2e/MMBtu Higher Heating Value.

equivalents, they were unable to gather molecule specific emissions factors (i.e. CO2 emissions, CH4 emissions, N2O emissions) for each use. For a complete picture of lifecycle emissions, this information is necessary as different studies used different GWP values for methane and nitrous dioxide emissions. To overcome this limitation, the authors disaggregated emissions from CO2e into molecule emissions when possible. When the CO2e constituents were unclear, the authors used CO2e emissions. This introduces some uncertainty due to changing GWP values for different greenhouse gas pollutants. In particular, the emissions benefits of replacing some types of coal with LNG may be higher, especially in the short term. However, as CO2 is the primary source of CO2e emissions for all sources examined, this uncertainty does not affect this paper's conclusions. Using unnormalized CO2e values from different studies is a widely practiced method in energy studies, despite the decreased accuracy [45–47]. Due to changes in GWP values over time, future LCA studies should clearly delineate constituent molecules.

To understand emissions from displacement by LNG in the electricity sector, sources are compared to a new natural gas combined cycle plant, which includes transportation emissions from liquefaction, tanker transport to each country, and regasification. This means we likely underestimate, rather than overestimate emissions from natural gas generation, since the average combustion emissions of existing natural gas plants in each country examined is higher than that of a new plant. If utilization of existing plants is increased instead of building a new plant, the emissions change associated switching to LNG would be lower than indicated in this study. The emissions associated with a natural gas plant displacing construction of a new coal plant would be lower due to the high efficiency of new coal plants compared to existing plants.

For the purpose of understanding emissions put to industrial and household uses, we analyzed upstream and combustion emissions for industrial, commercial, and residential applications normalized to Higher Heating Values (HHVs) for each fuel. Unlike the United States, coal consumption in studied countries is not dominated by the power sector, and is widely used for industrial applications and for space heating. Similarly, natural gas is used for multiple uses. HHVs are not appropriate when comparing electricity uses as natural gas can be more efficient than coal for electricity generation due to combined cycle technology; however, no such advantage exists for heating applications [48]. Normalizing coal used for heating and its potential replacement LNG to HHVs creates a useful proxy of emissions from industrial, commercial, and residential applications. Further normalizing these emissions into Bcf/day allows a comparison of the emissions changes from using LNG for heating use with other applications, such as electricity generation. In calculating the upstream emissions associated with coal use for heating, we averaged upstream emissions from Japan, South Korea, China, and India coal for electricity use divided by a heat rate of 10,000 btu/MWh. Individual heat rates for each country were not available, so this value was used as an indicative measure. As most emissions for HHVs come from combustion (~90%), the error introduced by this measure is minimal.

4. Calculating normalized lifecycle emissions changes from LNG

In the United States, recent studies have found that natural gas infrastructure leaks more methane than previously estimated by the US Environmental Protection Agency (EPA) [5,6]. As methane is a more potent greenhouse gas than carbon dioxide, methane leakage potentially undermines the climate benefits of coal to natural gas fuel switching domestically and abroad. Despite increased scrutiny, substantial uncertainty remains as to the amount of methane that is leaking. To test the impacts of different leakage levels on the LCA emissions of LNG exports, this study considers three leakage values: 1.45%, 2.93%, and 5.87%. This study does not explicitly account for methane leakage between LNG import terminals and final use, so these leakage scenarios are representative of both domestic and international lifecycle leakage rates for all scenarios.

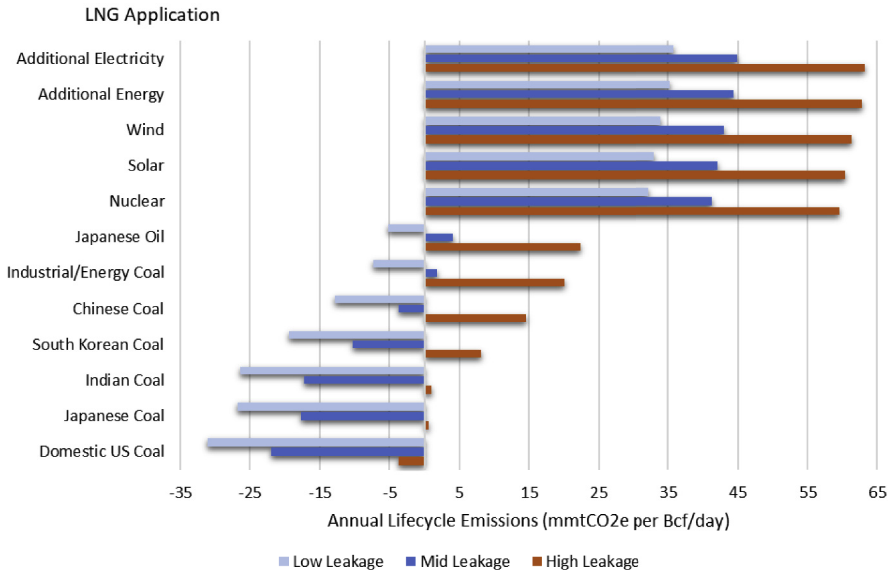
Lifecycle emissions across electricity and heating uses were pulled from scientific literature and normalized into the amount of that activity that would occur using 1 Bcf/day of LNG imports. The results of this normalization are presented in Fig. 2, which compares the direct emissions change that would occur with each identified application of LNG, with variations based on leakage rate scenarios. Here and elsewhere, we consider 20-Yr and 100-Yr global warming potentials (GWPs) to evaluate both short and long term climate impacts.

The potential net changes in emissions from 1 Bcf/day of LNG exports ranges from −32–63 MMTCO$_2$e, across leakage scenarios and timeframes. There are considerable variations in the benefits of replacing coal for electricity generation in each individual country. Replacing electricity from US coal with domestic natural gas brings higher climatic benefits than almost all LNG applications. Conversely, meeting additional electricity or energy demand using imported LNG has the greatest negative climate effect across all leakage scenarios and timeframes. This is due to no GHG emissions being offset in importing countries, leading to net emissions increasing.

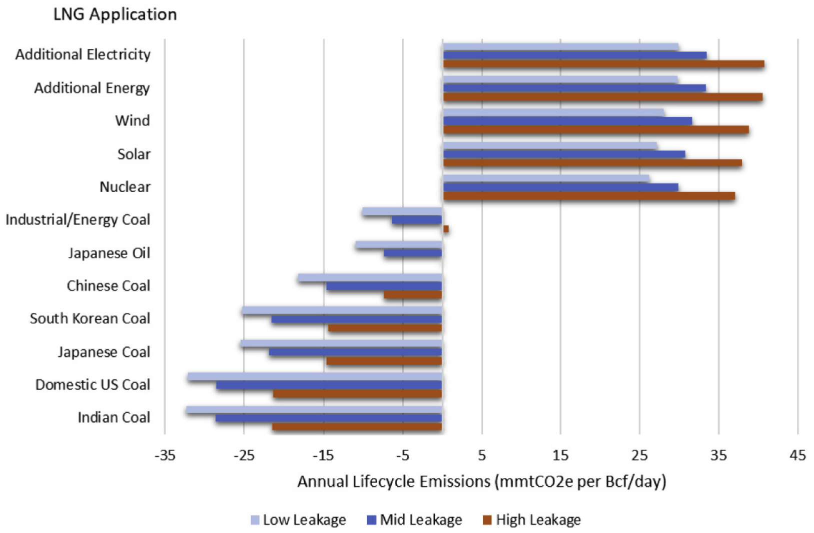
Leakage rates and GWP time frame choice greatly influence the estimated net climate impacts of exported LNG. Generally, the emissions benefits of replacing coal-fired electricity generation with LNG decrease significantly at higher leakage rates and when using a shorter GWP. Notably, our estimates indicate that the three uses of exported LNG with the largest potential to decrease net global emissions are replacing Indian, Japanese, or South Korean coal for electricity. However, replacement of these energy sources with LNG is not likely to happen at large levels because of each country's energy security goals, as explained earlier. Finally, using LNG to replace heating uses of coal (i.e. non-electricity industrial, commercial, or residential use) brings lower nets emissions benefits than replacing coal for electricity generation.

Fig. 3 bounds the potential upside and downside emissions from US LNG exports. The figure is scaled to 40 Bcf/day, the approximate amount of applications before DOE, with the current state of regulatory approval indicated. Note, as many applications are unlikely to be approved, 40 Bcf/day is likely much higher than maximum US LNG exports in the short or medium term. Positive Direct indicates decreases in emissions from use of LNG, bounded by replacement of Japanese Coal. Negative Direct indicates increases in emissions from use of LNG, bounded by meeting additional electricity demand. Negative Indirect are the emissions that could be reduced by using natural gas domestically to replace coal instead of exporting it. The actual emissions associated with LNG will most likely be somewhere between the ranges.

Projects with some level of federal approval could have the eventual potential to decrease emissions by 302 MMTCO$_2$e or increase emissions by 353 MMTCO$_2$e annually in the mid leakage and 100-Yr indicative scenario. The scale of net global emissions impacts from LNG exports depend on the magnitude of total LNG exports. Critically, using exported LNG domestically to replace coal instead of exporting it could reduce U.S. emissions by up to 300 MMTCO$_2$e.



a. 20-Yr GWP



b. 100-Yr GWP

Fig. 2. Net Emissions Resulting from Identified Applications of LNG. Note: Domestic US Coal is included for reference and refers to emissions saved from replacing coal for electric generation in the US with a new domestic natural gas combined cycle plant.

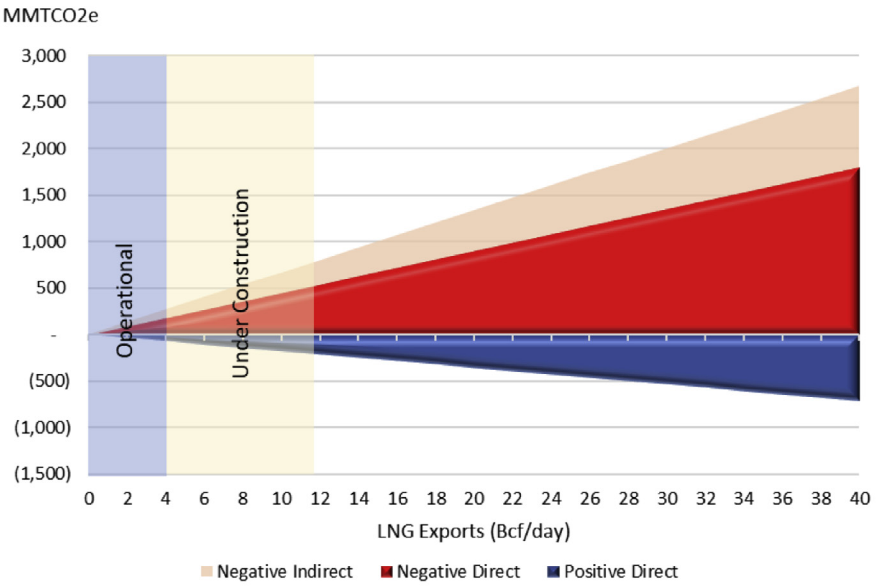
5. The aggravating factors: lost displacement and additionality

On a bounded technological LCA basis, our results indicate a spectrum of potential global net emissions outcomes of exporting LNG. However, the actual impacts are going to depend on natural gas impacts domestic and international energy markets. In domestic markets, LNG exports could lead to higher natural gas prices decreasing total natural gas consumption in the United States. In international markets, primarily the countries in this study, LNG exports could lower LNG prices and lead to greater LNG consumption. This could then lead to LNG displacing domestic energy sources or leading to higher overall energy demand.

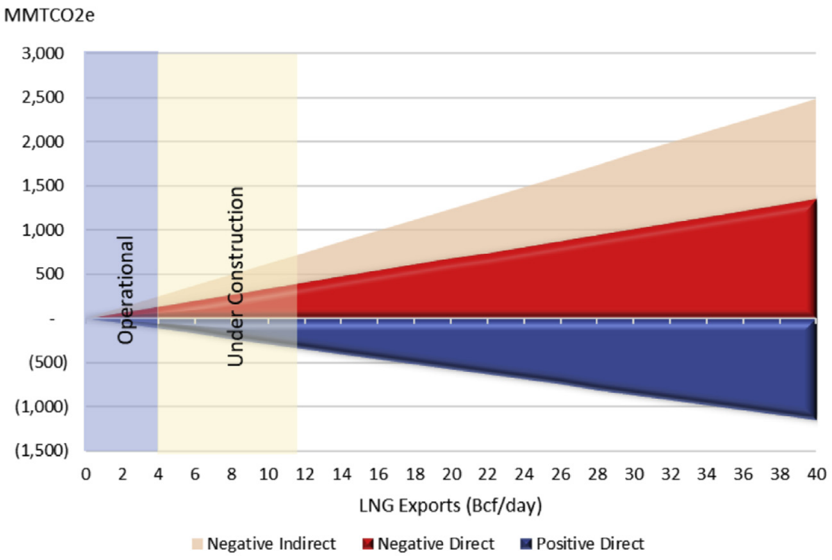
In 2012, the Energy Information Administration (EIA) analyzed how different levels of LNG exports would impact domestic fuel prices and energy use [39]. EIA's report indicated that LNG exports would indeed lead to higher domestic prices and less domestic natural gas consumption in all export cases. In the four scenarios examined EIA found that, between 2015 and 2035, an average of 65% of exported natural gas would be met by new domestic natural gas production. Meanwhile, 24% would come from reduced natural gas consumption by power plants and the rest would come from decreased consumption in other domestic sectors.

With natural gas and coal currently in competition for market share in the United States, EIA found that reduced natural gas generation from these exports would be met by higher coal generation.

Reducing domestic natural gas consumption impacts the net



a. 20-Yr GWP



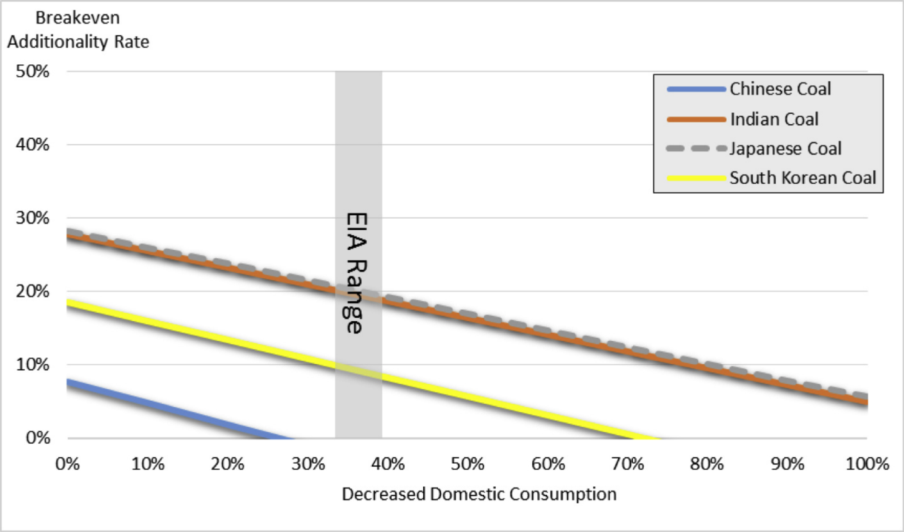
b. 100-Yr GWP

Fig. 3. Bounded Direct and Indirect Emissions of Proposed LNG Projects. Note: Mid Leakage Scenario. Replacing Indian coal for electricity generation was excluded from this bounding as it is highly unlikely to occur at significant levels.

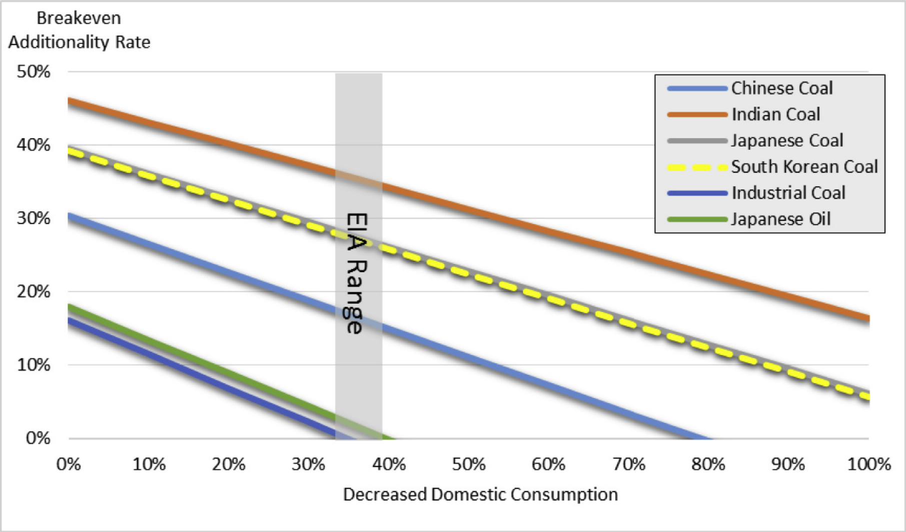
global emissions associated with LNG in three ways. First, liquefaction, transportation, and regasification lead to higher upstream emissions for the use of exported LNG compared to domestic consumption. Second, decreased domestic coal to gas fuel switching increases emissions. Third, emissions in the US would somewhat fall due to decreased natural gas consumption, although this effect is much smaller than the first two factors. On balance, based on EIA's study and likely behavior of energy markets, domestic lifecycle emissions would increase due to greater upstream emissions and higher coal use.

Just as LNG exports leads to reduced domestic natural gas consumption in several end-use sectors, new LNG supplies will lead to higher natural gas consumption in importing countries in multiple sectors. Natural gas demand could increase in electricity, industrial, residential, and commercial uses. If natural gas consumption rises, total energy consumption rises. This is additionality: exported US natural gas provides heating or electricity in importing countries but does not displace or replace other energy end uses. To the degree this energy consumption would otherwise not occur, the additional energy usage causes increased greenhouse gas emissions.

Decreased domestic gas consumption and additional international energy consumption combine to limit the range of potential climate outcomes from US LNG exports. Fig. 4 indicates the



a. 20-Yr GWP



b. 100-Yr GWP

Fig. 4. Breakeven Additionality Rate versus Domestic Consumption. Note: Mid Leakage Scenario. Only some LNG uses are plotted in Fig. 4, as the remaining uses would lead to greater emissions regardless of the additionality or domestic displacement rates.

breakeven additionality rate for lost domestic gas consumption for different LNG applications (i.e. the amount of LNG that would need to supply additional energy use at a domestic displacement rate for the climate benefits of LNG to be zero). Note: EIA's studies found that approximately 34–37% of exported LNG came from projected reductions in domestic natural gas demand. As most reduced natural gas consumption would otherwise replace coal, the emissions penalties from additionality effects for each LNG applications can be significant.

For example, if a LNG terminal exported 0.5 Bcf/day of natural gas, 34% of which came from reduced domestic coal to natural gas fuel switching, then all the exported natural gas would need to displace only industrial coal or Japanese oil to keep net global emissions to zero (100-yr GWP). If any of that LNG were to go to additional energy demand instead, emissions would increase.

This displacement versus additionality analysis reveals that exporting US LNG to Asia will only yield long-term climate benefits if exported LNG was used almost entirely to replace coal for electricity generation. However, the three uses of LNG that we identify have the greatest potential emissions benefits are the least likely to happen due to the energy strategies of importing countries. These uses are replacing Indian, South Korean, and Japanese coal for electricity generation – coal for industrial use in these countries does not yield the same potential emission benefits. While replacing coal with LNG for electricity generation in China could lead to emissions benefits, LNG is not likely to replace exclusively coal for electricity generation. If LNG replaces marginal amounts of zero carbon resources, moderate amounts of industrial coal, or leads to modest increases in energy demand, net global greenhouse emissions resulting from exporting LNG to China would be negative.

Our displacement-additionality analysis thus suggests that the most likely uses of US LNG exports would result in increases in global greenhouse gas emissions. Critically, this analysis indicates that the market impacts of LNG exports, both domestically and internationally, have very large impacts on total emissions changes.

Considering the multi-decade lifetimes of LNG infrastructure, and the need to reduce emissions greatly by 2050, even favorable assumptions for LNG exports indicate they may not a climate solution based on current technologies.

6. Conclusion and policy implications

Our hybrid lifecycle-energy strategy analysis, based on both emissions estimates and likely market effects, indicates that exporting LNG is likely to increase global greenhouse gas emissions. While uncertainty remains, methane leakage, additional energy demand, and decreased domestic coal displacement have the very real potential to undermine any prospective climate benefit in the long term. LNG exports lead to increased short-term climate emissions in most scenarios. Only with favorable assumptions which conflict with the energy strategies and needs of importing countries are there net climate benefits from LNG exports. With this in mind, we offer two conclusions.

First, policymakers, including regulators and legislators, must consider the complete climate ramifications of LNG exports. To date, FERC has refused to look at emissions beyond the facility fence-line. DOE, responsible for determining whether exports are in the public interest, has not comprehensively examined the full suite of factors impacting lifecycle emissions of exports. The factors it has examined are methodologically misleading. The sheer scale of potential LNG exports, corresponding increases in global emissions under the most probable scenarios, and lifetimes of LNG infrastructure make enhanced regulatory scrutiny not only necessary but imperative. Future LNG export facilities could become today's coal plants, where entrenched interests fight meaningful action to reduce climate emissions, with significant negative impacts on the global public.

Second, both technological and market changes could make LNG exports into a better climate mitigation technique. Aggressive actions to address emissions across the entire lifecycle can lessen or even reverse likely emissions increases. Methane leakage from natural gas infrastructure can be better monitored and controlled. Utilization of carbon capture and storage could reduce emissions from combustion and liquefaction processes. Most importantly, more detailed emissions profiles of importing countries could create policy roadmaps which ensure that natural gas replaces the highest emitting resources. If the US wants to export its natural gas to other countries in a climate friendly manner, it should ensure those countries have the technical capabilities and international obligations to reduce their emissions.

Third, the implementation of countries' Paris climate pledges could greatly impact emissions outcomes from U.S. LNG exports. While all importing countries in this study pledged to reduce their emissions or emissions intensity, it is unclear to what extent they will do so and what role U.S. LNG could play in helping them do so. South Korea and Japan's struggles with nuclear energy, as well as the critical role coal plays in their electric mix, could make it very hard for U.S. LNG to reduce emissions in either country. U.S. LNG may similarly have uncertain policy implications in both India and China as energy demand continues to grow in these countries and the relative nature of their Paris pledges could limit overall absolute emissions reductions. The US′ recent decision to leave the Paris agreement and emergence as an international climate pariah could present significant challenges to increased US LNG exports. The relationship between U.S. LNG exports and the Paris pledges in all four countries is thus a critical area for further research.

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