Liquefied Natural Gas Exports and Global Decarbonization: Synthesising Existing Evidence*

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November 2023

Abstract

The climate impacts of liquefied natural gas (LNG) exports from the United States are unclear, yet have been the subject of intense recent debate. I review and synthesise existing evidence from a lifecycle assessments of LNG export, finding that sensitivity to methane leakage is the key determinant of net emissions impact. I conduct a meta-analysis of the scientific literature on upstream methane leakage from U.S. gas production, finding that prevailing leakage rates suggest net emissions increases from LNG export. Additionally, I extract detailed scenarios from international energy pathway modeling to argue that LNG exports are incompatible with a global commitment to keep warming under 1.5 degrees.

Keywords: natural gas, lifecycle analysis, methane leakage

*This is an updated version of a working paper prepared in Summer 2023, while I worked as a Research Assistant at the Centre on Regulation and Markets, Economic Studies, Brookings Institution, under the supervision of Dr. Sanjay Patnaik. I would like to thank Professor Barry Rabe for his invaluable feedback on multiple drafts of this paper. I would also like to thank Dr. Sean Smilie for his clarifications regarding his research results over email correspondence.

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The North American natural gas industry has been billed by many as a "transition fuel," a clean fossil fuel which can replace dirtier coal and enable a lower-cost pathway to decarbonization. Natural gas advocacy groups like the center for LNG claim that "LNG will play a vital role in reducing worldwide carbon emissions." Even House Republicans proposing to deregulate LNG export claim it will result in "massive global carbon emissions reductions." The climate impacts LNG export will continue to bear consequences for policy in the wake of President Biden's January 2024 "pause" on pending approvals of new LNG export terminals and ongoing litigation, which has overturned the pause as of July 2024.

It is true that the United States has achieved significant emissions reductions over the past 15 years through a substitution of coal for natural gas, as have other countries. Ever since the ""shale revolution,"" the U.S. has gone from a net importer to a massive exporter of natural gas. Proponents now argue that cheap American gas should now be exported as liquefied natural gas (LNG), particularly to countries with high coal usage such as China, enabling them to reduce emissions by burning relatively-cleaner LNG instead.

However, the scientific evidence is not so straightforward. U.S. natural gas production leaks copious quantities of methane, a strong greenhouse gas, calling into question the benefits of a coal-to-gas strategy. International energy modeling suggests that the U.S. is overbuilding LNG export capacity, relative to a net-zero 2050. A range of other factors add to the complications of an LNG export strategy, including concerns of energy security and infrastructure lock-in in developing countries. Reviewing the literature, I find that expanding U.S. LNG export infrastructure is likely incompatible with global decarbonization and President Biden's climate goal of limiting warming to 1.5 degrees C.

Further, I also find that decision-making regarding LNG and U.S. natural gas production generally is impaired by a serious lack of data. The U.S. could remedy this by expanding methane monitoring efforts, drawing on progress made by private groups and environmental organizations. Finally, for federal agencies to fully understand the climate effects of new LNG infrastructure and accurately determine whether it is beneficial to the public, they could factor lifecycle emissions and climate damages into the planning, approval, and review processes for LNG terminals.

1 U.S. LNG Export Infrastructure Today

Today, the U.S. is the world's largest producer of natural gas, and was just shy of being the world's largest exporter of LNG in 2022. From the very first exports of U.S. LNG beginning in 2016, the U.S. has more LNG export capacity than any other country, at nearly 14 billion cubic feet per day (Bcf/day), projected to grow to 22 Bcf/day by 2027.

Still, proponents such as Paul Bledsoe at the Progressive Policy Institute (PPI) advocate further expansion of LNG export terminals. Bledsoe argues that U.S. LNG is a relatively clean fuel that can replace coal, particularly in the developing world, and thereby reduce global emissions.

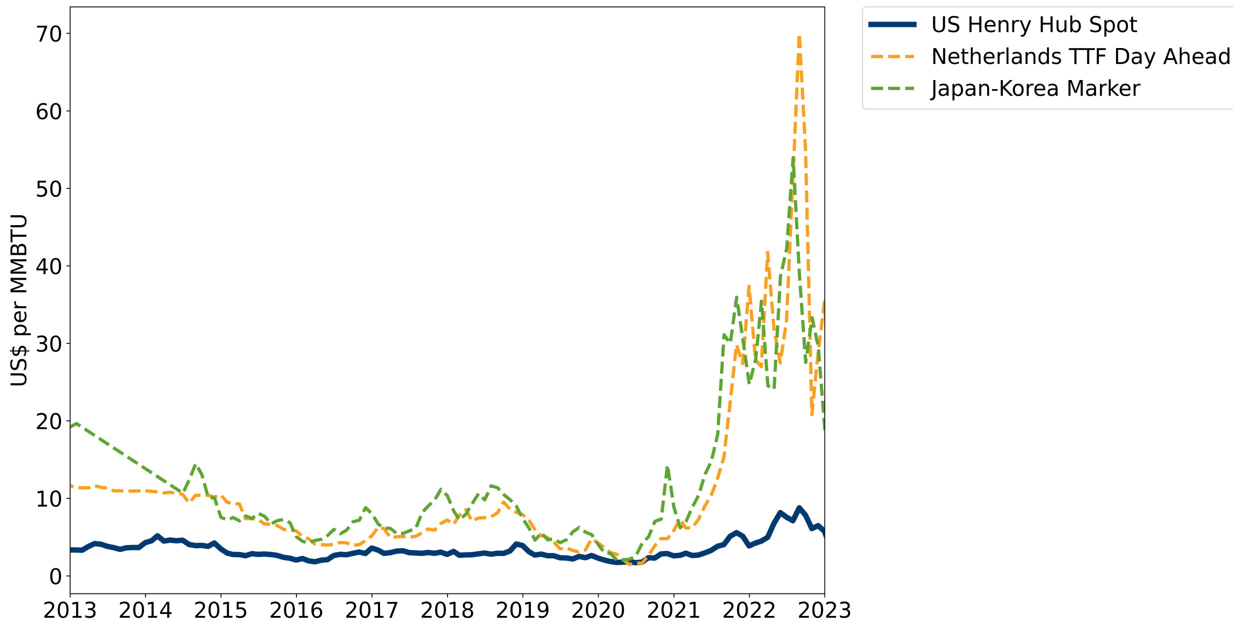
2 Potential Effects of U.S. LNG Export

The basic economics driving U.S. LNG exports is the fact that U.S.-produced natural gas is some of the cheapest in the world. Indeed, for over a decade, spot prices of U.S. gas (at the Henry Hub in Louisiana, the national benchmark) have remained well below comparable benchmark prices in Europe (at the Netherlands Title Transfer Facility) as well as in Asia (tracked by the Platts Japan-Korea Marker). These prices differences persist because the global market for natural gas is far less liquid than that for crude oil, for example. The U.S. already exports at nearly-peak capacity, so for U.S. gas producers to take advantage of higher global prices and export lower-cost U.S. gas to customers in Europe and Asia, new LNG export facilities would need to come online. Figure 1, below, shows global natural gas price benchmarks for the past decade.

FIGURE 1

Natural gas in the US is consistently cheaper than in Europe and Asia

Over the last decade, the U.S. gas price benchmark has been significantly lower than corresponding benchmarks in the Netherlands and East Asia



Source : Japan-Korea Marker from Platts, via Investing.com.
US Henry Hub spot price and Netherlands TTF Day Ahead from IMF Cross-Country macroeconomic statistics, via Nasdaq Data.

The logic of supply and demand would suggest, then, that new LNG export would drive *down* gas prices in Europe and Asia, while *increasing* prices in the U.S. This basic conclusion is backed up by a 2014 modelling study from scholars at the University of Maryland, as well as 2012 and 2014 analysis by the U.S. Energy Information Administration (EIA). With higher domestic prices and lower global prices of natural gas, there are multiple mechanisms by which net global emissions may increase or decrease.

2.1 Domestic Climate Effects

With higher domestic natural gas prices, gas consumers may shift to dirtier forms of energy such as oil or coal, or cleaner forms such as renewables. In 2012, the EIA estimated that increased LNG exports would be largely satisfied by increased gas production, accounting for 60-70% of exports, but that the remaining 30-40% of exports would existing gas production that is no longer consumed domestically, due to higher prices.

In its 2012 analysis, the EIA argued that higher domestic gas prices would cause the power sector to shift "primarily ... to coal-fired generation, and secondarily to renewable sources, though there is some decrease in total generation due to the higher price of natural gas." Even by 2021, when there was far less coal-powered electric capacity than in 2012, the EIA stated that higher domestic gas prices continued to cause increased U.S. coal consumption.

Higher domestic gas prices could be good for the climate in some ways, such by promoting the electrification of end-use gas applications like residential heating. It is unclear whether those benefits would outweigh the costs of increased coal consumption, however, and on net increased LNG exports seem likely to increase domestic emissions.[1]

2.2 Global Climate Effects

At present, emissions from the U.S. account for about 15% of the global total, making *global* climate impacts of increased U.S. LNG export more important than domestic effects. As stated previously, proponents of U.S. gas exports argue that LNG will displace foreign coal, and therefore reduce emissions.

International energy markets are not always so straightforward, however. Lower global natural gas prices and increased supply could, certainly, have a significant emissions reductions component as electricity generation plants either replace their coal boilers with gas boilers, or replace the plant entirely with a natural gas combined-cycle unit. Industrial users may make similar modifications. At the same time, lower gas prices could induce additional demand, especially in developing economies, wherein people *increase* their total consumption of energy in response to lower gas prices.

Furthermore, coal displaced by gas in one end-use, like electricity generation, may find its way to another end-use, like industrial heating. Lower gas prices could also weaken the competitiveness of renewables or nuclear, and thereby lead to increased emissions.

With these competing potential effects and mechanisms, both domestic and international, quantitative evidence is required to evaluate the relative sizes of the different effects, and therefore the net emissions impact of U.S. LNG export.

[1] It is important to note, in addition to climate effects, that nearly all planned LNG export projects are on the Gulf Coast of Louisiana and Texas, an already overburdened area with high cancer rates and poor air quality. LNG terminals have serious effects on air pollution, which many activists argue are ignored by regulators. Any expansion of LNG export terminals must reckon with the associated environmental justice consequences.

3 Quantitative Assessments of U.S. LNG Export Impacts

If we assume that coal is perfectly substituted for gas, on a one-to-one basis by energy consumed, there are a handful of empirical estimates that find U.S. LNG to be cleaner, under most circumstances, than other gas suppliers or domestic coal.

1. A 2015 study by Leslie Abrahams and co-authors found U.S. LNG to be cleaner than piped Russian gas and cleaner than local coal in Europe and Asia, for both electricity generation and industrial heating end uses.

2. A 2019 study from the U.S. National Energy Technology Laboratory (NETL) compared U.S. LNG exports to Shanghai and Rotterdam to LNG from Australia and Algeria respectively, as well as pipeline gas from Russia and local coal, and found that on a 20-year GWP, U.S. LNG was indeed the lowest emitter.

3. A 2021 study by Selina Roman-White and co-authors relied on EPA data (which is well known to be inaccurate) to argue that the LNG exported from the Sabine Pass Liquefaction terminal is cleaner than the national average, and far cleaner than coal in China. (Note that this study was funded by Cheniere Energy, the owner of Sabine Pass.)

While all these studies provide some evidence that U.S. LNG is generally cleaner than coal and Russian pipeline gas, they do *not* provide an accurate assessment of the real-world emissions impact of increased U.S. LNG exports. They simply provide estimates of what the emissions impacts *would be*, in a best-case perfect-substitution scenario.

There are also a number of studies that examine the very same question and come to decidedly mixed answers.

1. A 2018 study by Alexander Gilbert and Benjamin Sovacool assessed the range of potential impacts of US LNG exports to Asia. This study found that one-for-one substitutions of U.S. natural gas for coal or oil in Japan, China, India, or Korea, would result in substantial emissions *decreases*, but substitution for renewables or nuclear, or increased gas consumption as a result of increased supply, would lead to emissions *increases*.

2. A 2020 study by Yu Gan and co-authors shows that the emissions intensity of U.S. LNG consumed in China is higher than that for most other LNG sources,

as well as domestic Chinese conventional gas, but is lower than piped gas from Central Asia and Russia, and Chinese shale gas. However, uncertainties in this study are quite wide and overlapping.

3. A 2021 study by Kirsten Rosselot and co-authors found that different compositions of the supply chain have different climate effects. The cleanest American gas going to the most efficient Chinese gas plants could decrease equivalent emissions by 70%, but in the worst-case could increase it by 300%. This study suggests that it is impossible to say with confidence that the new US LNG is good for the climate without a closer look at the supply chains.

Therefore, while the first set of studies suggest that U.S. LNG may be cleaner than many alternatives under perfect substitution, the second set of studies qualifies that the substitution scenarios, choice of alternatives, and supply chains, are all critical to determining the net climate impact.

Further, it is highly unlikely that a perfect substitution of coal-to-gas will occur. More plausibly, some mix of positive and negative emissions impacts will occur, contingent on the relative market prices of LNG and other energy sources, the cost of coal-to-gas switching, and various other market effects, not to mention non-market factors such as the energy security goals of importing countries and geopolitical tensions. The impact of LNG export is highly contingent on the extent to which lower prices of natural gas causes LNG to displace dirtier fuels, versus the extent to which the lower prices induce additional consumption of gas.

The preceding argument is sharpened further with the consideration of a specific case study.

3.1 Case Study: Alaska LNG

Alaska LNG is the most recent LNG export facility to undergo environmental review. In early 2023, the Department of Energy released the final Supplemental Environmental Impact Statement (SEIS) for this project, which include a gas liquefaction and export facility in southern Alaska, and 800 miles of pipelines to transport gas from northern Alaska to the export facility.

The lifecycle analysis of this project factors in a major complication that has not been considered so far – the gas that would be supplied for export is co-produced with oil, and would otherwise have been reinjected into oil production wells in the North

Slopes of Alaska, and therefore the net greenhouse gas (GHG) emissions impact of LNG export is partially offset by the decline in oil production.

The Alaska LNG SEIS considers two bounding scenarios, providing upper and lower bounds for the impact of this project on the climate. In the **Emissions Lower Bound** scenario, total energy demand remains constant – in other words, the LNG that would be supplied by this project is supplied by alternative U.S. sources instead, and the reduction in oil produced in Alaska is met by the world market. The analysis finds that, since Alaska's natural gas is slightly cleaner than other U.S. sources, building this project would reduce emissions by around 250 million metric tons of CO2-equivalent (MMTCO2e).

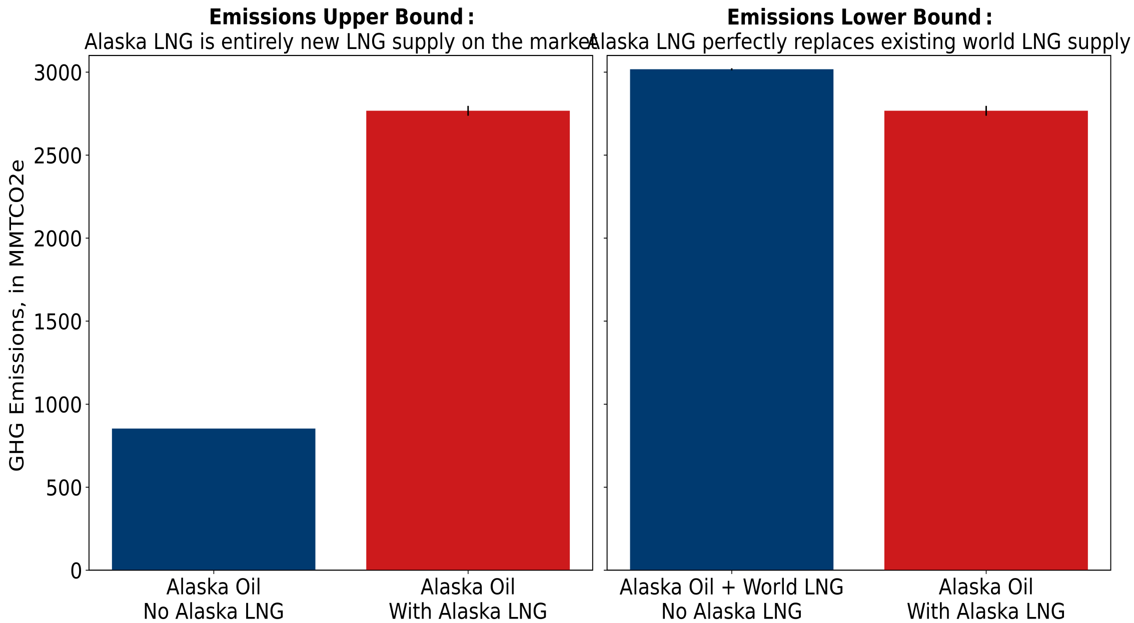
However, it is quite unlikely that the energy supplied in the world remains unaffected by the introduction of a large new LNG export facility. In the **Emissions Upper Bound** scenario, the SEIS considers the case that no new LNG supply is added to the market. That is, the LNG produced by Alaska LNG does not displace *any* existing gas production and represents completely new consumption. In this case, the analysis finds that emissions from the LNG exported by this project cause an approximately 1750 MMTCO2e *increase* in emissions.

In sum, if LNG from this project were to entirely displace other LNG, global emissions will fall by around 250 MMTCO2e. On the other hand, if it were to entirely supply new consumption, global emissions will *rise* by around 1750 MMTCO2e. Determining the true effect of LNG on the global climate is therefore clearly dependent, to a large degree, on market dynamics. As Figure 2 below demonstrates, market dynamics make the difference between a massive increase in emissions and a slight decrease in emissions.

FIGURE 2

Market dynamics determine if Alaska LNG will increase or decrease global emissions

In the Upper Bound scenario, Alaska LNG is assumed to supply entirely new LNG to the market, increasing emissions drastically. In the Lower Bound scenario, Alaska LNG is assumed to entirely substitute for dirtier world LNG, decreasing emissions slightly.



Source: Alaska LNG Final SEIS, U.S. DoE

3.2 Marginal Impacts of New LNG Projects

To our knowledge, only one study currently published accounts for *any* market effects is a 2022 "consequential" lifecycle assessment from Sean Smillie and co-authors at Carnegie Mellon University.

This study builds a partial-equilibrium market model of the world energy economy and estimates the impact of one additional North American LNG export terminal.

This study finds that, due to increased North American coal use, rebound increase in international gas consumption, and imperfect substitution of foreign coal to gas, the expected emissions benefits of LNG export are *far smaller* than previous estimates with perfect substitution have found, by a factor of nearly 6. Further, the wide uncertainty range of this study suggests that due to a new 2.1 Bcf/day LNG export facility, global emissions may fall by 40 MMTCO2e, or they may *increase* by 11 MMTCO2e.

The study finds that the net emissions impact of a new U.S. LNG project is predominantly dependent on the international elasticities of supply and demand for energy sources, foremost among them the rate of substitution of gas for coal and other energy sources. The elasticities of substitution are *far more important* than the theoretical emissions intensity of coal or gas. The market effects, in other words, are *first-order* – it is more important to assess how markets will react to new LNG, than it is to assess whether coal or various sources of gas are cleaner in a technical sense.

It is also important to note a major caveat of this study – the elasticities of substitution used based on historical data, and so do not reflect national policy goals of decarbonization or energy self-sufficiency. They are therefore likely to be even lower in the future than estimated in this study, further reducing the potential emissions savings of LNG export.[2]

3.3 Fugitive Methane and Coal Breakeven

In addition to the potential emissions gains from U.S. LNG exports being substantially reduced or erased by market effects, methane leakage from the LNG lifecycle has the potential to make exported LNG *worse* for the climate than coal.

Methane is the dominant constituent of natural gas and is a highly potent greenhouse gas. On a 20-year timescale, methane is 85 times worse as a greenhouse gas than carbon dioxide, and 25 times worse on a 100-year scale. Due to the urgency of the climate crisis in the short term, with the need to reduce emissions to net-zero by 2050 (less than 20 years away), I focus on 20-year effects for the remainder of this article.

Methane may leak out during any stage of the LNG supply chain, including upstream gas production, transmission, shipping, and distribution after landing at its destination. At some fraction of methane leaked for every unit of LNG supplied, LNG becomes a dirtier fuel than even coal.

The 2019 NETL study and the 2015 Abrahams et al. study provide estimates of the upstream "breakeven" leakage rate, above which LNG shipped from the U.S. is worse than coal for the climate. Estimates of breakeven rates vary significantly from 0% in Abrahams et al. (2015) for LNG used for industrial heating after distribution through a pipeline network, all the way up to a 6% rate, also from Abrahams et al. (2015), with LNG used for electricity generation without distribution through a pipeline network. These breakeven rates are summarized in Table 1 below:

Note that the Smillie et al. (2022) study and the wide range of the Alaska LNG study demonstrate that market dynamics are likely to be first-order factors. Furthermore, a recent estimate from RMI that factors in the effects of sulfur-dioxide

[2]The authors of Smillie et al. (2022) provided this caveat in personal communications.

emissions finds that under certain conditions, the breakeven rate may be as low as 0.2%. The above breakeven rates are therefore likely *over*estimates.

Still, these breakeven estimate ranges tell us that the potential climate costs or benefits of increased US LNG exports for coal-to-gas substitution are sensitive to estimates of methane leakage rates in the US. Unless the empirical data shows that methane emissions from U.S. natural gas production is convincingly below these breakeven thresholds, increased LNG export to replace coal in Europe and Asia appears likely to *increase* net global emissions. Therefore, I present below a summary of empirical estimates of upstream methane leakage rates in the U.S., at the national and regional levels.

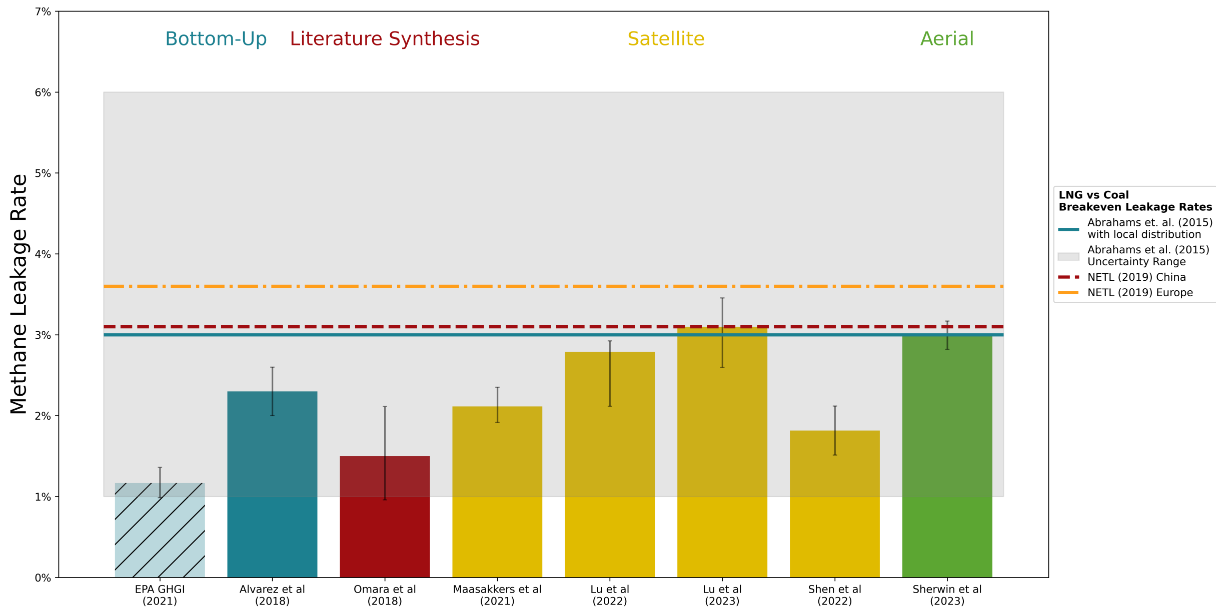
Figure 3A summarizes recent national-level U.S. upstream methane emissions rate estimates, compared to the central LNG-coal breakeven ranges. The two most recent estimates, from Lu et al (2023) and Sherwin et al (2023), have confidence intervals that solidly cross the NETL (2019) threshold versus Chinese coal, as well as the Abrahams et al (2015) threshold for LNG used for electricity generation with local distribution, versus coal. I include the EPA estimate for completeness, but it has been consistently found to be an underestimate.[3] All other empirical estimates are within the uncertainty range of the Abrahams et al. (2015) breakeven for electricity, with local distribution.

[3]Note that whether the estimates are bottom-up, from a synthesis of earlier literature, from satellite data, or based on aerial data, there are all substantially above the EPA rate.

FIGURE 3A

The uncertainty ranges of U.S. methane leakage rates and LNG-coal breakeven thresholds overlap

Bars represent estimates of methane leakage at the national level, organised by data source. Horizontal lines represent methane "breakeven" rates, above which LNG has higher GHG emissions than coal. Grey shaded area represents uncertainty breakeven range.



Source: Author-conducted literature review.

Notes: All estimates calculated assuming a conservative 90% methane content in natural gas produced. EPA GHGI estimate shaded as it has consistently found to be an underestimate in the literature

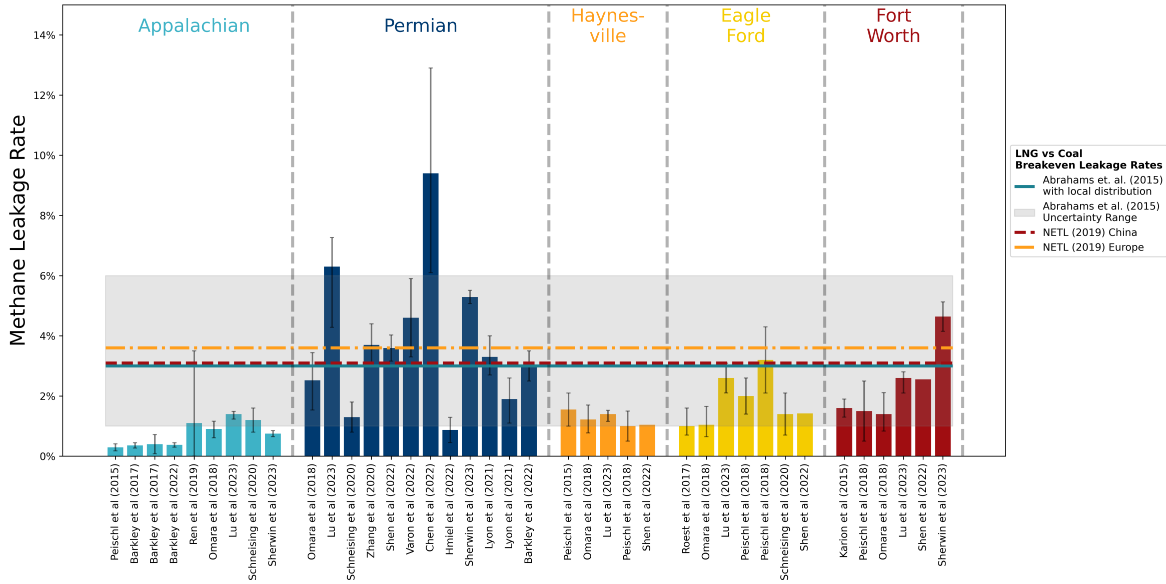
These findings are decidedly ambiguous – there is significant overlap in the uncertainty ranges of the breakeven rates and national leakage rates. Recall also that the breakeven rates are almost certainly overestimates. Therefore, this evidence does not indicate that U.S. LNG export is a clear climate benefit, and indeed suggests that it may be a net contributor to global emissions.

The above figures are national-level averages; estimates of basin-level methane leakage rates in the U.S. are even more worrisome. Figure 3B shows empirical estimates for the 5 largest shale gas producing basins in the U.S. (in decreasing order, they are the Appalachian, Permian, Haynesville, Eagle Ford, and Fort Worth basins). While some regions, like the Appalachian and Haynesville, have relatively low methane leakage rates, the Eagle Ford, Fort Worth, and (especially) the Permian regions fall close to or above LNG-coal breakeven thresholds. (Methane leakage rates for a larger set of regions is provided in the appendix.)

FIGURE 3B

Several major U.S. gas producing regions have methane leakage rates above LNG-coal breakeven thresholds

Bars represent estimates of methane leakage at the basin level, organised by data source. Horizontal lines represent methane "breakeven" rates, above which LNG has higher GHG emissions than coal. Grey shaded area represents uncertainty breakeven range.



Source : Author-conducted literature review.

Notes : Where not provided by author, estimates calculated assuming a conservative 90% methane content in natural gas produced. Estimates approximately arranged in chronological order of data collection year.

If new LNG export infrastructure is built and domestic natural gas prices rise, then, it matters how much various producing regions respond to the price signal. If Appalachian or Haynesville basin producers meet the global demand for LNG by increasing production, we are likely to see climate benefits. However, if instead the fast-growing Permian basin meets most of the demand for LNG, we are likely to see substantial increases in net GHG emissions.

I do note that the few studies that measured time trends in methane emissions found that practices improved over time and methane leakage rates fell; for example, Lu et al. (2023) found that national leakage rates fell from 3.7% in 2010 to 2.5% in 2019, and Varon et al (2022) found that leakage rates in the Permian fell from around 5.5% in 2018 to 3.5% in 2020. If these studies generalize and producers are generally improving their methane capture practices, it is possible that methane emissions rates will fall over time, and U.S. LNG export will become a relatively cleaner proposition.

However, if LNG demand is met not by the intensification of existing gas producing sites, but by the development of *new* sites, methane emissions are likely to increase even further. A range of studies have consistently found that newer gas productions sites have higher methane emissions rates.[4] Therefore, if prices rise and new production sites come online due to LNG exports, it is possible that methane emissions rates will rise even further.

Overall, then, there is substantial reason to doubt claims that U.S. LNG export would benefit the climate. A number of studies do find that U.S. national average emissions rates are above the coal breakeven, and even more find the same for multiple U.S. regions; methane emissions also vary over time and by the age of production area. There is therefore a high risk that expanding U.S. LNG export will *increase* net emissions.

3.4 Alternative Gas Suppliers

The above discussion centers on the tradeoffs between coal in Europe and Asia and U.S. LNG. However, one could reasonably counter that U.S. LNG should be compared primarily with alternative sources of gas. Especially given the Russian invasion of Ukraine and the consequent security concerns with Russian piped gas imports in Europe, proponents of LNG export argue that American gas is cleaner than Russian gas, justifying increased LNG export facilities.

Unfortunately, assessing such arguments quantitatively is challenging. In gas producing nations like Russia, Iran, and Qatar, there are few independent observations of methane emissions with aircraft overflight or ground-level measurements. Estimates of emissions rates can be done on the basis of data provided by companies and nations themselves, which is subject to bias, or on the basis of satellites, a growing field, but one that is as yet unable to provide comprehensive, high-reliability nation-wide methane emissions rates.

Still, given the information available, it is likely that Russian natural gas may be dirtier than U.S. LNG. It is supplied to customers in Europe (and, to a lesser extent, Asia) through long and often-leaky pipelines. Independent observers using satellites have detected massive methane leaks from Russian gas infrastructure, and external estimates of methane leakage far surpass official estimates from Gazprom. The Russian

[4] A 2020 study by Oliver Schneising and co-authors compared methane emissions rates for 2009-11 to 2018-19 and found declines, suggesting that newly-developing production sites have larger methane leakage rates than "mature" production sites. A 2021 study by David Lyon and co-authors found that the Permian Basin was in a state of "overcapacity" wherein higher prices and rapidly-growing gas production were associated with higher emissions rates of 3.3%, versus 1.9% when oil prices fell due to the COVID-19 pandemic. Similarly, a 2021 study in the Permian Basin by Itziar Irakulis-Loitxate and co-authors found that relatively new facilities were major methane emitters, and Zhang et al. (2020) found more extreme emissions from newer facilities.

government is notoriously unreliable in its reporting of emissions in general, regularly revising its official estimates of methane emissions downwards. Other gas sources in Central Asia are similarly dirty – a 2020 paper by Oliver Schneising and co-authors (cited in the Figure above) estimated methane leakage rates in Turkmenistan, from the two of the largest gas fields in the world, to be around 4.1%, and major leaks from Turkmenistan have been detected via satellite. Satellite observations from 2019-2020 found the most methane "ultra-emitters" in Turkmenistan, followed by Russia and the United States.

These conclusions should be treated with caution, however - according to Clark Williams-Derry, energy finance analyst at the Institute for Energy Economics and Financial Analysis (IEEFA), if we try to replace Russian gas with U.S. LNG, it is "plausible – not definite, but plausible — that we could wind up with a situation where U.S. methane leakage goes up more than Russia's goes down." There is some evidence from empirical studies to support this claim, suggesting Russian piped gas may not necessarily be higher-emitting than U.S. LNG.[5]

Furthermore, U.S. LNG should be compared not just to Russian piped gas, but also other exporters of natural gas to Europe and Asia. Norway is now Europe's biggest gas supplier, and its methane emissions rate is among the lowest in the world, at just 0.03%, due to a long history of tight standards and regulation.[6] Gas producers in the Persian Gulf like Qatar are likely relatively clean as well. In a 2022 study, RMI compared U.S. LNG shipments (assuming gas produced in the East Texas and Arkoma basins) to Germany to Qatari LNG and Russian piped gas. It found that, principally due to pipeline leaks, Russian gas caused nearly twice as many GHG emissions as U.S. LNG. However, U.S. LNG produces over 33% more GHGs than Qatari gas, due to higher upstream emissions as well as a longer pipeline network. The results from the RMI study are reproduced in Figure 4 below.

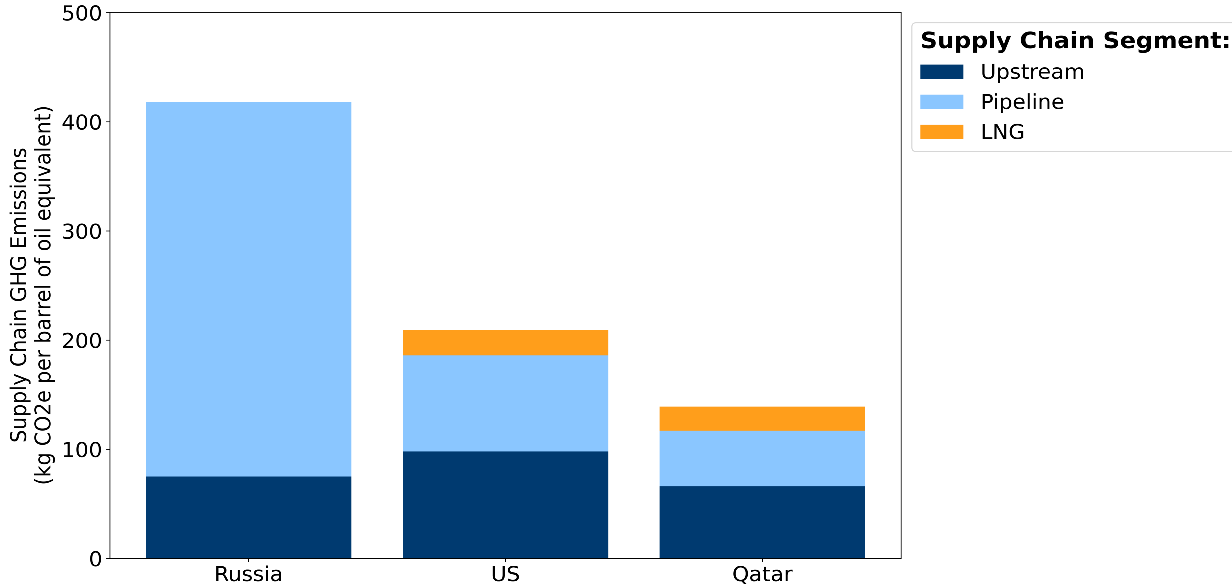
[5] A 2021 study by Cooper, Balcombe, and Hawkes estimates the total methane emissions from Russian pipeline exports to be 0.297% of gas supplied, while US LNG exports are estimated as leaking 1.495%. The 95% CI range for the US LNG estimate is (0.939%-2.730%), while that for the Russian piped gas is (0.183%-0.733%). The confidence intervals for these do not overlap.

[6] North Sea gas from Norway and the UK has been measured to have 98% flaring efficiency, which is the level that is often assumed for the U.S., although measurements find substantially lower efficiency.

FIGURE 4

Emissions Intensity of Gas Supplies to Germany

Data from RMI finds that LNG exported from Qatar to Europe is cleaner than either U.S. LNG or Russian piped gas to Europe



Source: Bylsma et al. (2022) at RMI.

Note: RMI selected Düsseldorf, Germany, as a proxy destination for EU imports of piped gas from Russia.

In summary, it is very difficult to conclusively argue that increased exports of U.S. LNG would be good for the climate. Few studies take into account market effects; the one that does returns highly uncertain results, and the case study of Alaska LNG concretely demonstrates that export projects may have positive or negative net emissions. Further, even without taking into account market effects, high methane leaks could make U.S. LNG dirtier than coal. And while U.S. LNG may be cleaner than piped natural gas from Russia or Turkmenistan, other suppliers like Norway (piped) and Qatar (LNG) can provide significantly cleaner alternative sources.

4 Role of U.S. LNG Export in a Net-Zero 2050

So far, I have tackled the question of increased U.S. LNG export at the margin. In this section, I will take another perspective, and instead consider the role of U.S. LNG in models of a decarbonized global economy. In particular, if the world is to avoid the worst impacts of climate change and achieve the target of limiting warming to 1.5 degrees C above preindustrial levels, or even the more permissive level of 2 degrees C, the Intergovernmental Panel on Climate Change (IPCC) has stated that the world much reach net-zero GHG emissions by 2050. In this section, I consider how U.S. LNG can fit into a pathway to a net-zero world.

A 2022 paper from Shuting Yang and co-authors finds that while there is some potential for coal-to-gas switching in the near term, long-term expansion of LNG infrastructure is not compatible with the IPCC pathways for 1.5-2 C warming. In the short-term, until 2035, if over 60% of LNG replaces coal rather than contributing to new consumption of gas, emissions are reduced. However, coal-fired capacity must decline rapidly by 2050 in a 1.5 C world. Beyond 2035, even 100% coal-to-gas substitution results in increased emissions from new LNG, because there is no more available coal to replace.

Furthermore, even if 100% of LNG replaces coal, there will not be enough coal capacity for LNG to replace very shortly. In a 1.5 C compatible pathway, this transition occurs in the year 2030, while for a 2 C pathway, it occurs in 2038. In other words, if the world retires coal plants at the pace required to limit warming to 1.5 C, then no new LNG export facilities should come online after 2030.

With lower, more realistic gas-to-coal substitution percentages, these transition years are likely to come even sooner. Coupled with the fact the global LNG capacity is projected to expand significantly over the next decade, this paper makes a clear case for why further expansion of LNG export infrastructure is unnecessary and counter to decarbonization targets, risking the creation of stranded assets.

Modeling from the International Energy Agency (IEA) suggests a similarly limited role for LNG. Indeed, in the World Energy Outlook of 2022, it specifically cautions that "No one should imagine that Russia's invasion can justify a wave of new oil and gas infrastructure in a world that wants to reach net zero emissions by 2050." It argues further that "Ultimately, however, the prospects for natural gas in emerging market and developing economies in Asia have a limited duration." In the IEA's Net Zero by 2050 Roadmap, "between 2020 and 2050, natural gas traded as LNG falls by 60%."

Figure 5 below illustrates how no further expansion of LNG capacity is consistent with the IEA's decarbonization scenarios. If countries decarbonize as they have pledged (the IEA's "Announced Pledges Scenario" [APS]), LNG traded remains well below existing and projected export capacity.

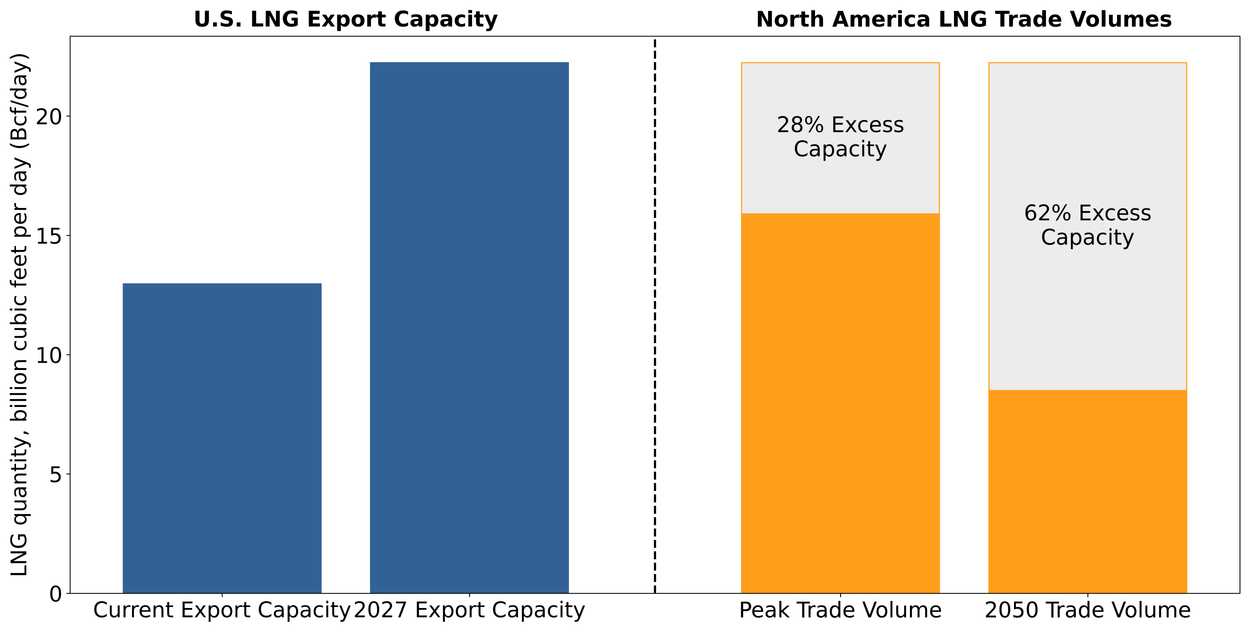
Under the APS, the IEA projects that LNG exports from North America must peak at 15.9 billion cubic feet per day (Bcf/day) in the 2030s, before falling significantly by 2050. The U.S. already has 13 Bcf/day of capacity, which will rise to 22.3 Bcf/day by 2027, with a further 2.5 Bcf/day added by Canada and Mexico. This represents significant excess capacity, of 28% in the 2030s and rising to over 60% by 2050.

In other words, by 2027, the U.S. will have more export capacity than all of North America needs for LNG trade until mid-century.

FIGURE 5

The U.S. does not need any more LNG export capacity

Projected LNG export capacity addition in the U.S. by 2027 is already in excess of total North American LNG trade volumes allowable under global decarbonization pledges



Source: Current U.S. export capacity from U.S. EIA.Projected 2027 export capacity from BloombergNEF. Peak and 2050 LNG trade volumes for all of North America, from IEA WEO 2022.

Notes: LNG export capacity in BloombergNEF in MTPA converted to Bcf/day using IEA conversion factor of 0.131584156. Projected capacity includes LNG terminals that are under construction, in commissioning, or expected to come to final investment decision in 2023.

In addition to the under-construction, in-commissioning, and expected final investment decision projects shown in the graph above, which add up to 10.3 Bcf/day of projected capacity by 2027, there is an even longer pipeline of excess proposed projects. According to the EIA, projects of capacity 14.65 Bcf/day have been approved by FERC and DOE, while a further 6.8 Bcf/day in U.S. capacity has been proposed but not yet approved by FERC.

The above depicted overbuilding of LNG capacity suggests one of two outcomes. Optimistically, these projects may run below-capacity as the world decarbonizes; older terminals may retire early. (For reference, in 2021 and the first half of 2022, U.S. LNG export ran at 87% capacity utilization on average.)

More realistically, however these projects are likely to take advantage of the arbitrage potential in global LNG and export at near-peak capacity, leading to a drop in global natural gas prices, increased natural gas consumption in addition to some coal-to-gas switching, and likely higher GHG emissions than accounted for by the IEA. In such a scenario, the world would not be able to decarbonize in accordance with its announced pledges, and the United States may be responsible for substantial excess emissions.

5 Other Factors Affecting U.S. LNG Export

In addition to the arguments presented above, wherein the marginal effect of LNG export is highly uncertain and the role of LNG export in a decarbonized future is highly limited, there are other factors that may limit U.S. LNG export capacity and affect the climate consequences of LNG infrastructure expansion.

5.1 Lock-In

The phenomenon of infrastructure 'lock-in' is a real danger from the construction of LNG facilities now. These facilities have investment payoff periods typically over a decade long and typical contract periods of twice that. With LNG terminals already slated to come online in 2025, developers will have a strong economic incentive to keep them in operation until 2045 at least, perpetuating the consumption of natural gas at a time when it would have to be declining to meet 1.5 C climate goals. Once LNG export terminals are built, natural gas import and consumption globally faces a lower marginal cost than before, potentially helping it outcompete renewables.

LNG export terminals built today could therefore become "stranded assets," running at below-profitable utilization factors, and developers or policymakers may be unwilling to retire them early while absorbing the associated economic losses. The large capital costs, long timelines, and social and political dependencies associated with fossil fuel infrastructure, all create constraints towards decarbonization.

Further, the expansion of natural gas infrastructure across the world concurrent with LNG export terminals, may have long-term emissions consequences inescapably embedded, even if that infrastructure ends up underutilized. Natural gas pipelines across the European Union leak methane, for example. "Orphan" wells, oil and gas wells that have been abandoned, continue to leak methane into the atmosphere. The construction of LNG export facilities and the concurrent expansion of associated infrastructure, including production, processing, storage, transport, distribution, and consumption, is likely to leave leaky infrastructure in place for decades, contributing to global emissions even if we reduce the end-use of fossil fuels.

In this context, the construction of LNG export facilities may cause "lock-in" to a pathway of high natural gas production in the U.S., and high gas consumption in the rest of the world, potentially slowing progress towards decarbonization.

5.2 LNG Demand & Energy Security in Developing Countries

After the Russian invasion of Ukraine, as global gas prices spiked (visible in Figure 1), European countries outcompeted Asian importers of LNG. Energy became more expensive and developing countries learned that imported LNG is an unreliable, volatile fuel. While proposed LNG export capacity additions would reduce costs for these importers, countries may prioritize domestic energy sources to insulate themselves from global price fluctuations.

Key among these are the large Asian economies of India and China, which have announced large expansions of coal power capacity. Both countries have stated that they aim to be entirely self-reliant in energy production. China in particular has recently ramped up its domestic coal mining and generation capacity, in response to 2021 power shortages and recurring heat waves. These countries are among the largest producers of coal in the world, but both depend heavily on import for their supply of natural gas. Further increasing their reliance on imported LNG would contradict their stated policies of self-reliance.

Given these factors, there may be limited appetite in Asian economies to substitute significantly replace domestic, "secure" coal with imported, "insecure" LNG.

Further, the coal-to-gas transition advocated by proponents of LNG export often requires substantial capital investment on the part of developing-economy importers. These countries must either build new natural gas capacity or must replace coal boilers with natural gas boilers. These investments, as well as the continued import bill for LNG, can crowd out investments in renewables, according to a 2021 report by IEEFA. Thus, pushing LNG export may cause a spillover increase in climate impacts, due to avoided renewables investment.

An important caveat to this point, however, is the significantly lower air quality consequences of natural gas, as against coal. Developing Asian countries have some of the worst air quality in the world, in part due to coal consumption. Transitioning from coal-based heating and cooking to natural gas, and coal power plants to gas power plants, could therefore have sizeable benefits for air pollution. China's steady air pollution reductions over the past years are at least partly attributable to a coal-to-gas transition. Given the massive health and economic costs of air pollution in Asia, even if there are little to no climate benefits, LNG-fueled coal-to-gas transitions may be a good strategy to reduce air pollution.

5.3 Energy Security in Europe

The ultimate demonstration of the volatility of natural gas supply was on display with the Russian invasion of Ukraine and subsequent cutoff of Russian gas imports to Europe. Providing energy security to the U.S.'s European allies is frequently cited as a good reason to increase LNG export capacity.

Even after the invasion of Ukraine, however, the E.U. managed the cutoff of Russian gas with existing tools. It saw a 13% reduction in natural gas demand in 2022, the steepest drop in history according to the IEA, partially thanks to a mild winter but also in large part due to increased supply of renewables, behavioral changes to reduce usage, and industrial production curtailment. The EU also ramped up import of natural gas from other sources, including pipeline imports from Norway, Algeria, Libya, Azerbaijan, the UK, and LNG imports from the U.S. and Qatar.

Furthermore, the EU has pledged to cut natural gas demand 60% by 2030. As part of its REPowerEU plan in response to the invasion of Ukraine, the EU plans to mobilize €300 billion, 95% of which is for the clean energy transition. With strong commitment, significant funding, and a track record of successful climate action, there is good reason to consider the EU targets credible, and therefore expect significantly lower EU natural gas demand in the 2030s.

Therefore, since EU gas consumption can already be met with existing global capacity and gas demand is likely to decline over time, new U.S. LNG capacity is unlikely to play any real role in securing the E.U. from Russian gas dependency.

6 Policy Considerations and Recommendations

The research in this article reveals that increased U.S. LNG exports are unlikely to meaningfully advance global decarbonization or energy security for Europe or Asia, principally due to high methane emissions in U.S. gas production, and the need for a rapid global transition to renewable sources of energy. In this section, I discuss the policy and regulatory context surrounding the approval of U.S. LNG facilities. I provide options for regulators and Congress to limit the future emissions impact of

U.S. LNG.

6.1 LNG Export Planning and Approval

The regulatory process for LNG export involves multiple agencies. The most important agency is the Federal Energy Regulatory Commission (FERC), which, according to section 3 of the Natural Gas Act of 1938, has "the exclusive authority to approve or deny an application for the siting, construction, expansion, or operation of an LNG terminal." Essentially, FERC is in charge of permitting the *infrastructure* for LNG terminals. FERC also leads the environmental review of LNG terminals, under the National Environmental Policy Act (NEPA).

However, the export of the gas itself is regulated by the Department of Energy (DOE). The Natural Gas Act specifies a two-track approval process for gas export, depending on the trade relationship of the export destination with the U.S. For countries that have a Free Trade Agreement (FTA) with the U.S., LNG export is automatically deemed to be "in the public interest" and approved; for non-FTA countries, the DOE must permit export unless the proposed exports are not "consistent with the public interest."[7]

The DOE relies on macroeconomic analyses commissioned every few years to conclude that LNG export is consistent with the public interest. The most recent analysis was performed in 2018, by an economic consultancy firm. Notably, the analysis makes no reference to emissions or climate change and does not factor in any "public interest" against environmental damages such as air pollution and climate change, both of which cost the U.S. billions of dollars in health and weather-disaster costs. Indeed, the DOE process for non-FTA LNG export has been criticized as a "rubber stamp" approval by environmental organizations and some members of Congress. It has never denied an application for LNG export.

However, the Natural Gas Act does not state that "public interest" must be limited to consideration of the macroeconomy. As I have shown in this article, LNG export may cause net GHG emissions, depending on the export destination, end-use, and source of gas; the damages of these GHG emissions affect the U.S. public significantly, with over $150 billion in climate damages in 2022 alone. Therefore, the Biden administration could direct the DOE to commission a new public-interest analysis of LNG export, and mandate that it factor in considerations of climate change

[7] There are 20 countries with which the U.S. has a free trade agreement (FTA), for which no DOE permit is needed. For non-FTA countries, DOE must authorize the quantity of gas to be exported.

and environmental justice.

If new LNG liquefaction facilities *are* approved, they could be planned while factoring in early retirement. The IEA has argued that when evaluating such projects, developers and policymakers should consider "shortening the period of capital recovery, making the delivered gas more expensive, and planning from the outset how to extend emissions reductions across the whole value chain." The DOE typically issued permits for LNG export for 20 years, but after a change made under the Trump administration, all permits go to the year 2050. The Biden administration could modify this policy and direct the DOE to time-limit future permits for LNG export while factoring in a global decarbonization schedule.

In addition, for any new LNG liquefaction facilities, the Biden administration and FERC could ensure that their Environmental Impact Statements (EIS) contain full consequential lifecycle analysis estimates of the project's GHG emissions. Prior to the Alaska LNG project SEIS cited in this paper, estimates of GHG emissions were only provided for construction and operation emissions, which are a small fraction of the total emissions an LNG project is responsible for. To the extent possible, future EISs could factor in a range of possible market and policy effects to determine the extent to which the project may increase or decrease global emissions.

FERC can draw upon multiple resource for how to incorporate such considerations. In early 2022, FERC put forth a new framework and draft policies to expand the consideration of GHG emissions and environmental justice in the review process for natural gas infrastructure. The draft policy allows for the consideration of upstream GHG emissions, for example. In addition, FERC may draw upon the White House Council on Environmental Quality's January 2023 Interim Guidance on the consideration of climate change in NEPA reviews.

6.2 Methane Regulation

It is important to note that the analysis of U.S. LNG as compared to other international suppliers and other fuels in this article is based on present-day methane emission rates. Under the Biden administration, the U.S. has made a series of steps towards controlling methane leakage, and it is possible, though highly conditional, that it may go from a global laggard to a leader on methane leakage. I summarize some of the key current and prospective avenues of methane-control policy below. Further, I describe how a strong methane regulatory framework could serve as a prerequisite for any LNG expansion.

In November 2021, the EPA proposed new regulations on methane emissions from the oil and gas industry (which it then supplemented a year later.) In its latest version, the EPA forecast that this regulation would reduce methane emissions by 87% by 2030, relative to 2005 levels. It would also improve monitoring of well leaks, documentation of plugging of abandoned wells, introduce a "super-emitter" monitoring program, add regulations to flaring, and strengthen methane standards for other parts of the oil and gas production process. (It is important to note, however, that like other parts of the Clean Air Act, states would be in charge of developing methane control plans and enforcement, leaving some uncertainty in the degree of success of these regulations. They may also be affected by future litigation or rollback under changed Presidential administration.)

While the EPA methane regulations are strong, there remains some room for further improvement. For example, the EPA regulations do not prohibit routine flaring, unless there is no route to sales, off-site or on-site use possible; by contrast, Canada's proposed regulatory framework prohibits routine flaring entirely. The EPA regulations also would not directly limit gas venting, while Canada would eliminate venting. Together, excess venting and flaring are major sources of methane emissions, and the EPA could go further in limiting them. According to Jim Krane at Rice University, one way to do so would be to extend existing rules requiring "green completions" of oil and gas wells, and prohibit *all* flaring a certain number of days after completion of a well, barring an emergency. Further, mirroring regulations in place in Alaska, the EPA could mandate the filing of a report for all instances of flaring and venting.

In addition to EPA methane regulations, the forthcoming methane fee may also reduce the climate impact of natural gas and LNG. In August 2022, President Biden signed the Inflation Reduction Act (IRA), which enacted a landmark methane fee of $900 per metric ton in 2024, rising to $1,500 per ton in two years, on major parts of the oil and gas supply chain. Importantly, the IRA methane fee kicks in only on emissions above 0.2% of natural gas sold for production and processing facilities, 0.11% for transmission, and 0.05% for gathering, storage, and LNG facilities.[8] These rates set important benchmarks for fugitive methane, which are well below current emissions rates. However, if the original EPA regulations from November 2021 (or regulations bringing about equivalent emissions reductions) are implemented, the

[8] For facilities that produce no natural gas, the fee is 10 metric tons of methane per million barrels of oil sent to sale.

EPA can waive the methane fee. While it is too soon to know if this novel policy tool will be effective, it appears likely to reduce methane emissions in concert with EPA regulations.

Another regulatory step that would reduce methane leakage is a proposed Bureau of Land Management (BLM) rule from November 2022, which would require oil and gas producers operating on federal lands to reduce the venting and flaring of natural gas, or pay royalties for vented and flared gas. In effect, this rule would reduce methane emissions for the 10% of U.S. gas production and 25% of oil production which occur on federal lands.

In another step towards methane leak control, the IRA provided \$1.5 billion for oil and gas methane abatement technologies, while the 2021 Infrastructure, Investment, and Jobs Act provided \$4.7 billion for abandoned well remediation.

On the international level, the U.S. and European Union (EU) led a loose international effort to limit methane with the 2021 Global Methane Pledge, targeting a 30% reduction in methane emissions by 2030, relative to 2020 levels. The Pledge is non-binding, however, and contains no specific targets or actionable steps for countries; instead, it asks them to develop methane reduction plans.

Some states, led by New Mexico and Colorado, have implemented their own methane control regulations, with provisions including monitoring and reporting requirements, venting and flaring limitations, and independent monitoring programs. However, unconventional oil and gas operations (or "fracking"), which is now the majority of U.S. production of oil and gas, is highly mobile. States may therefore be unwilling to regulate methane emissions too strongly, for concern that oil and gas producers will simply move out of their state. Therefore, while state regulation could continue to serve as a laboratory for federal regulation, federal regulation appears essential for achieving strong methane leakage reductions.

The emergence of LNG projects in western Canada and planned LNG projects in Mexico further underline the importance of U.S. methane regulation and international collaboration on methane policy. In the case of Mexico, planned LNG projects seek to exploit the proximity of northern Mexico to U.S. gas production regions, and plan to import U.S. natural gas by pipeline, and then re-export it as LNG. Domestic methane regulation would help ensure that U.S. gas, whether exported through American or Mexican LNG terminals, is less damaging to the climate. In the case of Canada, strong forthcoming methane regulation framework and robust provincial emissions standards for LNG projects in western Canada are a strong start. Collaboration on methane control could help disseminate best practices, with U.S. and Canadian regulators learning from each other. Further, developing shared resources to monitor upstream methane emissions through satellites could lower costs.

Overall, with the recent wave of legislative and regulatory activity, the U.S. is well-placed to drastically cut its methane emissions. If the IRA's methane fee or EPA regulations go into effect, funding for abatement and remediation is well-utilized, and other federal and state regulations are implemented and well-enforced, it is possible that in the future, the U.S. could achieve levels of substantially lower levels of methane emissions. In such a scenario, LNG export in the short-term would be relatively more likely to be beneficial for the climate; therefore, ensuring the implementation and enforcement of methane regulation could be a critical pre-requisite for responsible LNG capacity expansion.

One way to structure a regulation-linked future for LNG capacity would be EPA certification of methane emissions performance. EPA (or delegated state agency) inspections of gas production facilities could certify compliance with methane regulations, and estimate venting, flaring, and leakage rates. Gas producing firms may then refer to this certification in their export marketing. The federal government's involvement in methane certification would likely replace the private LNG certification schemes already proliferating, which are reportedly of dubious reliability.

6.3 Methane Monitoring

As this article has highlighted, there are extremely wide uncertainty ranges on the key variables of interest in determining the climate effects of LNG export, including the upstream methane emissions rates of U.S. gas production, the breakeven methane emissions rates, and the emissions impacts of specific projects.

In addition, methane leak monitoring may help U.S. oil and gas comply with upcoming European import regulations. Europe is an important customer of American LNG, accounting for 64% of exports in 2022, mostly driven by the end of Russian natural gas sales to Europe following its invasion of Ukraine. The European Union may soon implement a methane standard on imported gas, mirroring a recent E.U. push for domestic methane regulation from the oil and gas industries. These new standards may include leak detection and repair requirements, or potentially even a maximum fugitive methane emission rate. Methane emissions monitoring may also help U.S. exporters cater to European importers interested in "certified" clean LNG, to meet their own commitments to environmental responsibility, as described in the previous section.

Therefore, for multiple reasons, improved methane emission data collection efforts would be a public good. For starters, federal efforts could build on independent methane monitoring initiatives, including the satellite-based Environmental Defense Fund's (EDF) MethaneSAT and Kayrros, satellite- and aerial-based CarbonMapper, and mobile laboratory-based Stanford/EDF's Mobile Monitoring Challenge. These could be supported and scaled up with federal grants, to ensure independent verification of methane emissions numbers. The U.S. could also expand financial and technical support and collaboration with the International Methane Emissions Observatory, a U.N. Environment Programme body dedicated to methane measurement. Another short-term measure with immediate benefits would be to deploy federal support to understaffed and underfunded state-level methane control efforts.

In the longer term, the EPA's methane emissions estimates, which are widely accepted to be drastic underestimates, could be systematically revised. The current EPA Inventory could be supplemented with a program of EPA-administered or EPA-funded aerial, satellite, and mobile-laboratory monitoring of oil and gas methane emissions. Nonprofits like the Environmental Defense Fund have so far shouldered the primary burden of methane monitoring; the EPA could now reassume its primary role in monitoring methane emissions.

6.4 Global Decarbonization

Finally, efforts to aid decarbonization internationally should focus on expansion of renewables, not LNG. The Biden Administration should accelerate bilateral efforts like the U.S. International Development Finance Corporation's loans for solar projects in India and the US-India Clean Energy Finance (USICEF), and multilateral financing efforts like the Just Energy Transition Partnership to decarbonize Indonesia.

7 Conclusion

U.S. LNG exports do not appear to be the global climate solution that natural gas proponents make it out to be.

High levels of methane leakage in many gas fields make U.S. LNG exports comparable to coal in net emissions. In addition to significant heterogeneity in methane leakage rates between gas fields, the emissions effect of LNG exports depends on market effects and substitution, energy security policies, the emissions profile of alternative gas suppliers (many of which are far cleaner than the U.S.), and the role of infrastructure path dependency. Further, the U.S. has a large pipeline of LNG export terminals approved and expected online in the next decade. However, International Energy Agency modeling suggests that U.S. natural gas exports must peak around 2030 and decline significantly by 2050, to achieve a net-zero future. Therefore, further U.S. LNG capacity expansion is inconsistent with global decarbonization.

Additional U.S. LNG capacity is also not necessary to meet European demand following the cutoff of Russian gas imports, nor is it compatible with the energy security goals of major developing Asian economies. I also note that LNG terminals are unlikely to find a future as liquified hydrogen terminals, due to the very different properties of hydrogen and natural gas.

The evidence presented in this article could be adopted by U.S. regulatory agencies in multiple ways. Environmental reviews of LNG terminals under NEPA could include consequential life-cycle analysis of the project's climate impacts; the DOE could redo its public-interest analysis of LNG export, incorporating expected climate damages; the EPA could expand its methane monitoring programs, and strengthen methane leak regulations. Finally, U.S. support for global decarbonization could focus on renewable energy, rather than natural gas.

8 Appendix

A complete regional meta-analysis of methane leakage rates in the U.S. can be found in the online Appendix figure linked here.