U.S. LNG in transition: An analysis of supply chain emissions from the nation's largest export facility and potential for abatement.

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Abstract

Exporters of liquefied natural gas face growing pressure from buyers and end-user nations to address supply-chain emissions of greenhouse gases. This pressure has led to the trade of "carbon-neutral LNG cargoes," which involves accounting for emissions associated with a cargo that customers can then use to purchase carbon offsets. However, analyzing supply chain emissions remains a significant challenge in the absence of more accurate emissions monitoring or an industry-wide standard for estimating emissions.

This research paper uses a framework adopted in the first trade of a "carbon neutral cargo" sourced from the largest U.S. LNG export facility, Cheniere's Sabine Pass LNG terminal, to produce a new estimate of annual emissions associated with U.S. LNG exports before the point of export. The result provides a useful reference point for analyzing domestic supply chain emissions associated with the sector.

Next, the Sabine Pass facility is used as a case study to analyze facility-level emissions. Estimates of annual facility-level emissions at the terminal are shown to be about 41% higher than what official U.S. government inventories estimate. The research then turns to an economic analysis of deploying carbon capture and storage at Sabine Pass to abate estimated emissions. This analysis shows that incremental operating cash flow before debt repayment could become positive in 2030 with proposed increases to carbon-capture-and-storage incentives under the Section 45Q tax credit that U.S. lawmakers are considering at the time of this writing. If credits could cover operational expenses, justifying a $4 billion capital cost of carbon capture and storage could depend on a combination of Cheniere's ability to bring in additional revenue as a

result of a competitive advantage gained through the abatement investment and on the value to the company of avoiding risks such as the potential for stranded assets.

Acknowledgements

I am grateful to my project mentor, Brett Mudford, for his guidance, support, time, and patience. Brett's expertise in the natural gas sector, in financial analysis, in project management, and in fundamental research principles all proved tremendous resources in helping me shape and execute this research project. I also would have struggled to produce this project without the resources provided to me by employer, S&P Global Market Intelligence, including a wealth of natural gas and financial data.

Contents

Table of Units and Abbreviations

LNG	Liquefied Natural Gas
CCS	Carbon capture and Storage
BBB	*Build Back Better Act*
CO2e	Carbon dioxide equivalent
tonne	A metric ton
EIA	U.S. Energy Information Administration
Bcf	Billion cubic feet
IEA	International Energy Agency
EPA	U.S. Environmental Protection Agency
mtpa	Million tonnes per annum
GIIGNL	International Group of Liquefied Natural Gas Importers
Mt/y	Million tonnes per year
BEIS	U.K. Department of Business, Energy, and Industrial Strategy
Dth/d	dekatherms per day

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Executive Summary

As the U.S. moves closer to becoming the world's largest exporter of liquefied natural gas (LNG), growing concern about planet-warming emissions throughout the natural gas supply chain has led to uncertainty about the role of the fuel in a future that meets emissions-reductions targets of the Paris Agreement[1]. It has become clear that emissions in the U.S. LNG value chain must be addressed.

Concern over the climate footprint of LNG supplies has given rise to the trade of "carbon-neutral LNG" cargoes, which involve accounting for emissions associated with a cargo that customers can then use to purchase carbon offsets that absorb equivalent emissions from the atmosphere. A key challenge for the small-but-growing carbon-neutral LNG trade remains the need for monitoring and reporting improvements to accurately account for emissions[2]. LNG cargoes labeled as "carbon neutral" do not by themselves reduce emissions, and it is increasingly clear that the next, more difficult challenge will be achieving emissions reductions amid rising anti-gas sentiment in policymaking and investment circles[3].

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[1] UNFCCC. (2021, November 13). *Glasgow Climate Pact*. United Nations Framework Convention on Climate Change. Retrieved from https://unfccc.int/documents/310475.

[2] Blanton, E. M., & Mosis, S. (2021, July 8). *The Carbon-Neutral LNG Market: Creating a Framework for Real Emissions Reductions*. Columbia University's Center on Global Energy Policy. Retrieved August 15, 2021, from https://www.energypolicy.columbia.edu/research/commentary/carbon-neutral-lng-market-creating-framework-real-emissions-reductions.

[3] Paul, C., & Weber, M. (2021, June 9). *Natural gas in transition: Emissions-conscious markets weigh on US LNG'S Future*. S&P Global Market Intelligence. Retrieved August 15, 2021, from https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/natural-gas-in-transition-emissions-conscious-markets-weigh-on-us-lng-s-future-64822177.

This paper calculates an estimate of annual CO2 equivalent supply-chain emissions associated with the largest U.S. export facility – Cheniere's Sabine Pass LNG terminal in Louisiana – using a framework adopted in the trade of a "carbon neutral cargo" sourced from the facility. Estimates of facility-level emissions under this approach are shown to be significantly greater than what official U.S. greenhouse gas emissions inventories estimate.

Next, this paper explores pathways for abating facility-level emissions that the company could pursue, identifying the deployment of carbon capture and storage technology (CCS), as the most viable option from a direct-investment perspective.

Finally, this paper produces an analysis of projected cash flow for the Cheniere unit that owns the Sabine Pass LNG export terminal to examine the potential financial impact on the subsidiary, as shown in fig. 13. The cash flow analysis factors in existing CCS incentives available under the Section 45Q tax credit and proposed increases to the tax credit under the *Build Back Better Act (BBB*) being considered at the time of this writing by Congress[4]. CCS costs are estimated to range from about $85-tonne of CO2 equivalent (CO2e) to about $91/tonne of CO2e. That range would likely fall once an additional liquefaction unit undergoing test work reaches completion because of an increase in captured CO2e and tax credit revenue, which offsets an increase in operating expenditures. This analysis shows that incremental operating cash flow before debt repayment could become positive in 2030 with the higher tax credit levels proposed in the *BBB*. If CCS incentives can cover operational expenses, an added $4 billion of debt could be viewed in the following ways: as additional revenue Cheniere that would need to

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[4] U.S. Congress. (2021, November 19). *H.R.5376: Build Back Better Act*. Congress.gov. Retrieved November 26, 2021, from https://www.congress.gov/bill/117th-congress/house-bill/5376.

bring in through a competitive advantage gained from the abatement investment, as an investment in avoiding lost revenue in a more carbon-constrained world, or as a mix of the two.

Introduction: The rise of U.S. LNG exports, and growing concerns over supply-chain emissions

Liquefied natural gas is produced by supercooling methane from natural gas to -161°C, for a roughly 600 times reduction in volume from the fuel in its gaseous state[5]. This cooling process, which uses a liquefaction unit known as a train, makes it possible to transport natural gas in specialized maritime tankers to places that are not interconnected by gas pipeline infrastructure. As LNG, the fuel can be shipped to overseas markets with specialized receiving terminals, where LNG is then regasified for combustion or transportation and storage in end-user markets.

The development of LNG export infrastructure in the United States has provided a critical outlet for domestic natural gas production, with the country becoming the world's largest producer of natural gas since the shale gas revolution that began in the 2000's[6]. S&P Global Platts estimates that demand for gas supplies by U.S. LNG export facilities, known as feedgas demand, will be the single-largest driver of growth in domestic production in the next 20 years[7].

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[5] DOE. (2021). *Liquefied Natural Gas (LNG)*. U.S. Department of Energy. Retrieved November 1, 2021, from https://www.energy.gov/fecm/liquefied-natural-gas-lng.

[6] Ibid.

[7] Paul, C., & Weber, M. (2021, June 9). *Natural gas in transition: Emissions-conscious markets weigh on US LNG'S Future*. S&P Global Market Intelligence. Retrieved August 15, 2021, from https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/natural-gas-in-transition-emissions-conscious-markets-weigh-on-us-lng-s-future-64822177.

Platts and many other forecasting agencies also suggest natural gas and LNG will remain critical for meeting global energy demand through mid-century[8].

The first exports of LNG from the U.S. Lower 48 came in February 2016 with a cargo from Cheniere's Sabine Pass LNG terminal in Louisiana, which was delivered to end users in Brazil[9]. In the more than five years since then, through October 2021, the U.S. has exported a total of more than 9 trillion cubic feet of natural gas as LNG to a total of 37 other countries with more than 2,800 cargoes shipped[10].

There are now six major U.S. LNG export terminals operating in the U.S., including Sabine Pass, which began producing LNG from the facility's sixth liquefaction train on Nov. 23, 2021[11]. Two additional LNG export facilities are under construction and expected to come online by mid-decade[12]. The U.S. Energy Information Administration (EIA) has estimated that the U.S. will become the largest exporter of the fuel in 2022, once the sixth Sabine Pass train and another facility under construction in Louisiana, Venture Global's Calcasieu Pass LNG terminal enter commercial service[13]. The EIA has forecast that these facilities will increase the country's peak

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[8] S&P Global Platts Analytics. (2021, February 24). *Future Energy Outlook: Annual Guidebook 2021* .

[9] *DOE. (2021, November 15). LNG Monthly. U.S. Department of Energy. Retrieved from https://www.energy.gov/fecm/articles/lng-monthly-2021.*

[10] *Ibid.*

[11] Cheniere. (2021, November 23). *Cheniere partners announces achievement of First LNG at Sabine Pass Train 6*. Cheniere Energy Partners, L.P. Retrieved from https://cqpir.cheniere.com/news-presentations/press-releases/detail/214/cheniere-partners-announces-achievement-of-first-lng-at.

[12] EIA. (2021, December 2). *Natural Gas Weekly Update*. Retrieved from https://www.eia.gov/naturalgas/weekly/archivenew_ngwu/2021/12_02/

[13] Ibid.

LNG production capacity from 11.6 Bcf/d as of November 2021 to 13.9 Bcf/d across the combined seven export facilities, meaning the U.S. will overtake Australia (11.4 Bcf/d) and Qatar (10.3 Bcf/d) as the biggest global LNG producer[14].

[14] Ibid.

Figure 1: Global LNG exports by country, from BP Statistical Review of World Energy 2021[15]

Natural gas: LNG exports

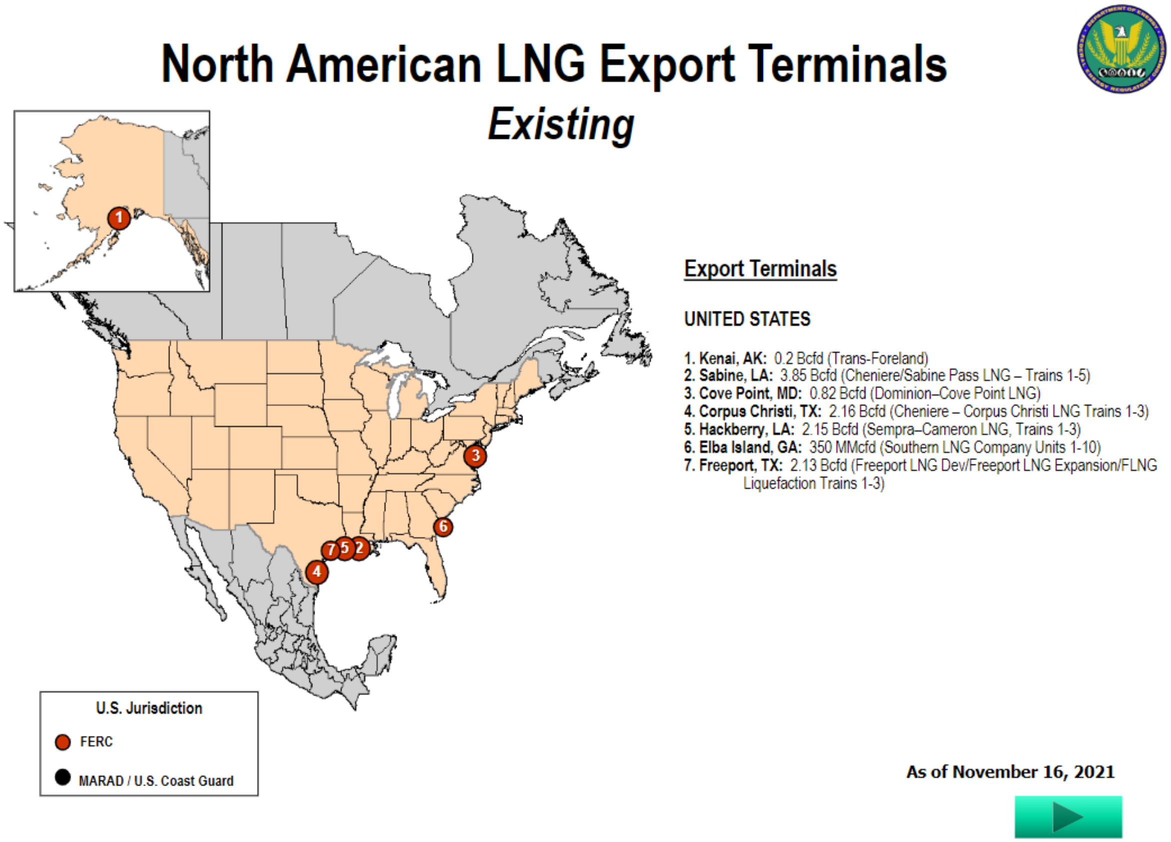
Billion cubic metres	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Growth rate per annum 2020	Growth rate per annum 2009-19	Share 2020
US	1.5	1.8	0.8	0.2	0.4	0.7	4.0	17.1	28.6	47.4	**61.4**	29.2%	50.1%	12.6%
Peru	1.9	5.2	5.1	5.7	5.7	5.0	5.5	5.5	4.8	5.3	**5.0**	-4.9%	n/a	1.0%
Trinidad & Tobago	19.6	18.2	18.3	18.4	17.6	16.4	14.3	13.5	16.6	17.1	**14.3**	-16.3%	-1.3%	2.9%
Other Americas*	–	0.1	0.5	0.1	0.2	†	0.6	0.3	0.1	0.1	**0.5**	392.3%	n/a	0.1%
Total Americas	22.9	25.2	24.7	24.3	23.9	22.1	24.5	36.5	50.1	69.9	**81.3**	16.0%	13.2%	16.7%
Russia	13.5	14.3	14.3	14.5	13.6	14.6	14.6	15.4	24.9	39.1	**40.4**	3.1%	19.0%	8.3%
Norway	4.6	4.4	4.6	3.8	4.6	5.6	6.1	5.4	6.8	6.9	**4.3**	-37.8%	8.2%	0.9%
Other Europe*	0.5	1.7	3.6	5.2	8.4	5.4	4.5	2.5	5.0	1.9	**1.3**	-29.3%	22.7%	0.3%
Total Europe & CIS	18.6	20.4	22.4	23.5	26.6	25.6	25.3	23.4	36.7	47.9	**46.0**	-4.1%	16.7%	9.4%
Oman	11.7	11.0	11.1	11.5	10.6	10.2	11.0	11.4	13.6	14.1	**13.2**	-6.3%	1.7%	2.7%
Qatar	77.8	100.7	104.0	105.8	103.6	105.6	107.3	103.6	104.9	105.8	**106.1**	♦	7.4%	21.7%
United Arab Emirates	8.7	8.3	8.1	7.9	8.6	7.6	7.7	7.3	7.4	7.7	**7.6**	-1.0%	-0.2%	1.6%
Yemen	5.5	8.8	7.1	9.9	9.4	1.9	–	–	–	–	**–**	n/a	-100.0%	–
Total Middle East	103.8	128.7	130.3	135.2	132.2	125.4	126.0	122.3	125.9	127.5	**126.9**	-0.8%	5.9%	26.0%
Algeria	19.5	16.7	14.9	15.0	17.4	16.6	15.5	16.4	13.1	16.6	**15.0**	-10.3%	-2.5%	3.1%
Angola	–	–	–	0.4	0.4	–	0.9	5.0	5.2	5.8	**6.1**	5.4%	n/a	1.2%
Egypt	10.0	9.0	6.9	3.9	0.4	–	0.8	1.2	2.0	4.5	**1.8**	-60.4%	-10.0%	0.4%
Nigeria	24.1	25.7	27.9	22.5	26.1	26.9	24.6	28.2	27.9	28.8	**28.4**	-1.5%	6.0%	5.8%
Other Africa	5.3	5.0	4.6	5.2	5.0	5.0	4.4	4.9	5.5	5.5	**5.1**	-7.5%	0.2%	1.0%
Total Africa	58.8	56.4	54.2	47.0	49.5	48.5	46.2	55.7	53.6	61.2	**56.4**	-8.1%	0.9%	11.6%
Australia	25.8	26.0	28.3	30.5	32.0	39.9	60.4	76.6	91.8	104.7	**106.2**	1.2%	15.3%	21.8%
Brunei	9.0	9.6	9.2	9.5	8.6	8.7	8.6	9.1	8.5	8.8	**8.4**	-4.2%	-0.3%	1.7%
Indonesia	32.4	28.7	24.4	23.1	21.7	21.6	22.4	21.7	20.8	16.5	**16.8**	1.6%	-4.8%	3.4%
Malaysia	31.0	33.2	31.4	33.6	34.0	34.3	33.6	36.1	33.0	35.2	**32.8**	-6.9%	1.5%	6.7%
Papua New Guinea	–	–	–	–	5.0	10.1	10.9	11.1	9.5	11.6	**11.5**	-0.9%	n/a	2.4%
Other Asia Pacific*	–	–	–	0.1	0.2	0.8	0.5	0.8	0.6	0.5	**1.4**	163.9%	n/a	0.3%
Total Asia Pacific	98.3	97.5	93.3	96.8	101.5	115.5	136.4	155.4	164.3	177.2	**177.3**	-0.3%	6.8%	36.3%
Total LNG exports	**302.4**	**328.3**	**324.9**	**326.8**	**333.6**	**337.1**	**358.3**	**393.3**	**430.6**	**483.8**	**487.9**	**0.6%**	**6.8%**	**100.0%**

Gross LNG trade.
*Largely consists of re-exports.
♦Less than 0.05%.
†Less than 0.05.
n/a not available.
Note: Growth rates are adjusted for leap years.

Source: includes GIIGNL, IHS Markit.

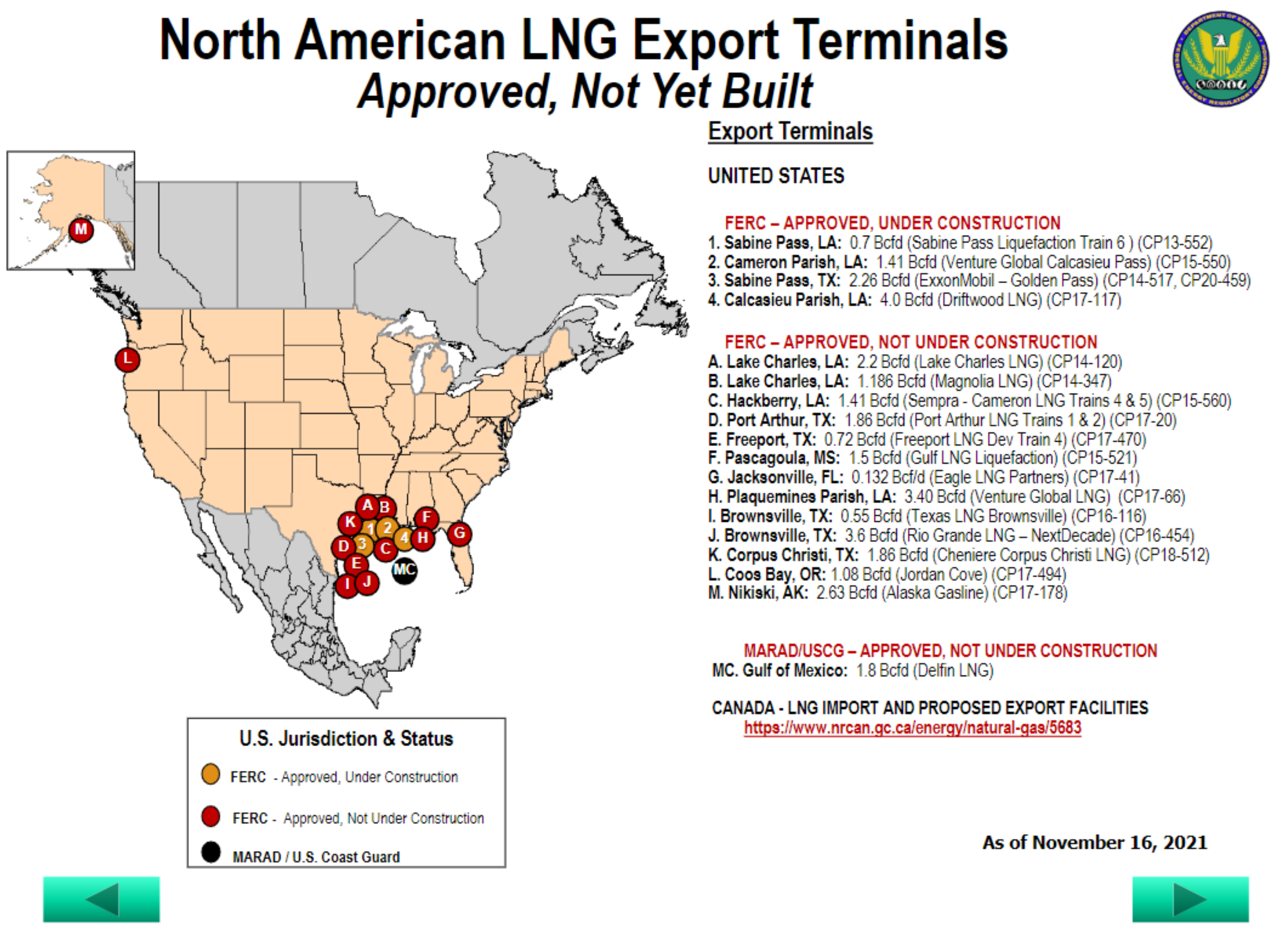
[15] BP. (2021). *BP Statistical Review of World Energy 2021*.

Figure 2: Existing US LNG export projects[16]



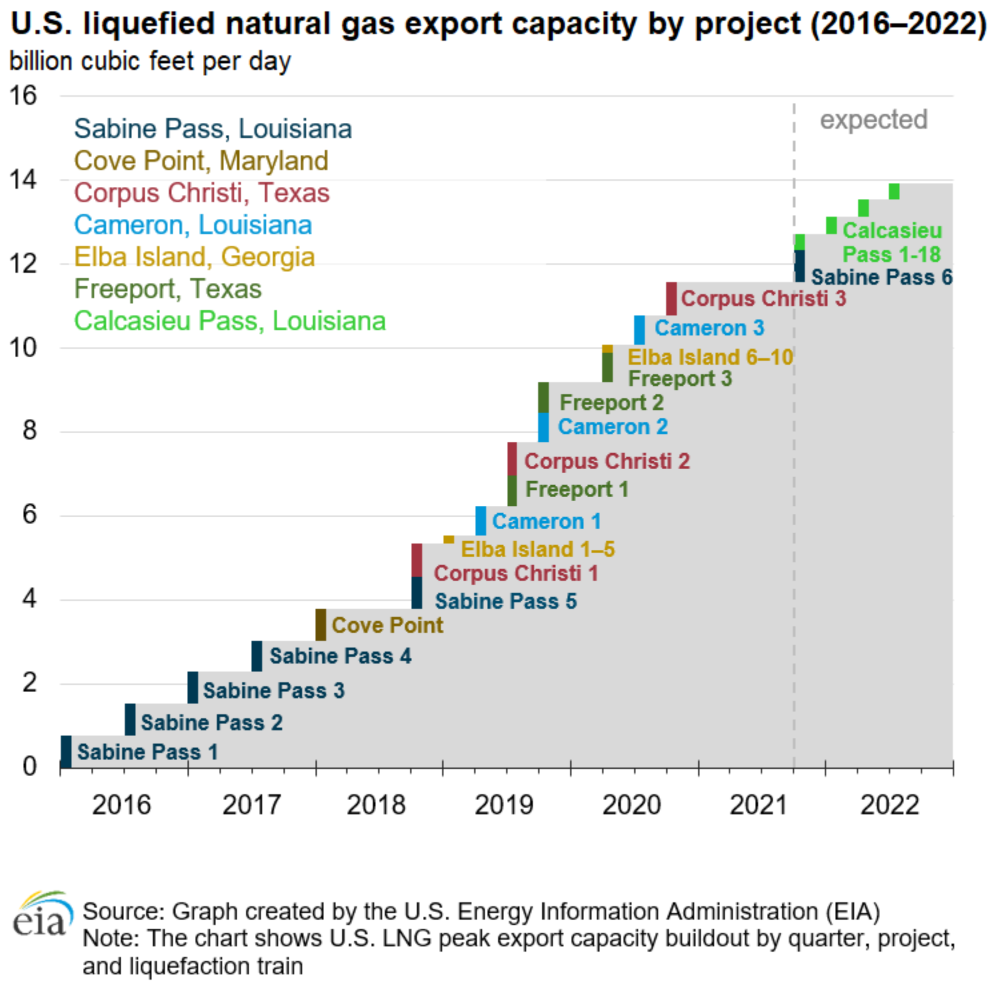
[16] FERC. (2021, November). *North American LNG export terminals – existing, approved not yet built, and proposed*. Federal Energy Regulatory Commission. Retrieved from https://cms.ferc.gov/media/north-american-lng-export-terminals-existing-approved-not-yet-built-and-proposed-2.

Figure 3: Additional LNG export projects approved by U.S. regulators for construction[17].



[17] Ibid.

Figure 4: Growth in U.S. LNG production capacity, EIA forecast[18]



Project sponsors have proposed about a dozen other U.S. LNG export facilities[19]. Developers are competing to sign sufficient long-term contracts with LNG buyers to underpin the financing

[18] EIA. (2021, December 2). *Natural Gas Weekly Update*. Retrieved from https://www.eia.gov/naturalgas/weekly/archivenew_ngwu/2021/12_02/.

[19] Paul, C. (2021, September 15). *LNG project tracker: Momentum Builds 'at least for a couple' of export projects*. S&P Global Market Intelligence. Retrieved November 29, 2021, from https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/lng-project-tracker-momentum-builds-at-least-for-a-couple-of-export-projects-66572867.

required advance their multi-billion dollar projects to construction[20]. Many of these projects already have the necessary federal permits[21], but market constraints mean that few are likely to get built[22].

Growth of U.S. LNG exports have helped the U.S. develop deeper economic ties with trade partners and lower trade deficits[23], strengthen the U.S. economy and bolster the energy security of allied nations by offering a competitive alternative natural gas supply to supplies from rival nations such as Russia[24].

Energy security benefits are indeed significant, particularly for energy-hungry buyers in Asia motivated by price and reliability concerns[25]. Buyers in China and other Asian countries are viewed as key drivers of market demand growth and already represent some of the top historical buyers of U.S. LNG[26]. This is in part because of a geographical concentration of major LNG importers and a geographical concentration of LNG exporters that has incentivized buyers to

[20] Ibid.

[21] FERC. (2021, November). *North American LNG export terminals – existing, approved not yet built, and proposed*. Federal Energy Regulatory Commission. Retrieved from https://cms.ferc.gov/media/north-american-lng-export-terminals-existing-approved-not-yet-built-and-proposed-2.

[22] Paul, C. (2021, September 15). *LNG project tracker: Momentum Builds 'at least for a couple' of export projects*. S&P Global Market Intelligence. Retrieved November 29, 2021, from https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/lng-project-tracker-momentum-builds-at-least-for-a-couple-of-export-projects-66572867.

[23] The U.S. Department of Energy reported that U.S. LNG exports in 2020 would reduce the country's trade deficits by $12 billion, even with market upheaval caused by the coronavirus pandemic, while also supporting thousands of jobs (DOE, 2020).

DOE. (2020, December 31). *Department of Energy Extends Fourth Set of LNG Export Authorizations Through 2050*. U.S. Department of Energy. https://www.energy.gov/articles/department-energy-extends-fourth-set-lng-export-authorizations-through-2050.

24 Collins, G., & Mikulska, A. (2021, February 12). *Gas Geoeconomics: A Strategy to Harden European Partners Against Russian Energy Coercion*. Rice University's Baker Institute for Public Policy. https://www.bakerinstitute.org/media/files/files/0fb54354/bi-brief-0211221-ces-geoeconomics.pdf.

[25] Paul, C. & Weber, M. (2021, February 11). Asia is key growth area for U.S. LNG even after 2020 impacts, market experts say. S&P Global Market Intelligence. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/asia-is-key-growth-area-for-us-lng-even-after-2020-impacts-market-experts-say-62614768

[26] DOE. (2021, November 15). *LNG Monthly*. U.S. Department of Energy. Retrieved from https://www.energy.gov/fecm/articles/lng-monthly-2021.

seek diverse sources of supplies. The five top importers in Asia in 2019 accounted for 62% of the world's LNG imports, and the top four exporters — Qatar, Australia, the U.S. and Russia, in descending order of volumes — accounted for 62% of the world's total LNG exports[27].

Proponents of LNG exports also point to the potential of the fuel as a bridge to low-emission energy sources because it releases fewer planet-warming emissions per unit of combustion energy than any other hydrocarbon fuel and it can be used as a baseload electricity generation source to complement variable renewable sources[28]. Natural gas is the cleanest burning hydrocarbon[29], with combustion of natural gas emitting about 50% less carbon dioxide than combustion of coal and about 30% less than combustion of oil per unit of energy delivered, while also releasing fewer other pollutants[30]. Accordingly, coal-to-gas switching has been viewed as an opportunity to rapidly reduce greenhouse gas emissions and is often favorably cited by proponents of LNG exports. A 2019 analysis by the International Energy Agency (IEA) estimated that 98% of natural gas has a lower lifecycle emissions intensity than coal when combusted for power or heat, estimating average reductions of 50% when used to produce power

[27] BP. (2021, June). *Statistical Review of World Energy 2020*. BP. https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html .

[28] Tagliaferri, C., Clift, R., Lettieri, P., & Chapman, C. (2017, March 9). *Liquefied Natural Gas for the UK: A life cycle assessment.* The International Journal of Life Cycle Assessment. Retrieved November 30, 2021, from https://link.springer.com/article/10.1007/s11367-017-1285-z.

[29] EIA. (2021, November 28). *How much carbon dioxide is produced when different fuels are burned?* U.S. Energy Information Administration. Retrieved from https://www.eia.gov/tools/faqs/faq.php?id=73&t=1.

[30] C2ES. (2020, July 13). *Natural gas*. Center for Climate and Energy Solutions. Retrieved November 30, 2021, from https://www.c2es.org/content/natural-gas/.

and of 33% when used to produce heat[31]. The IEA's analysis accounted for emissions of both CO_2 and CH_4, the primary component of natural gas.

However, the notion of using natural gas as a short-to-medium decarbonization strategy has come under greater scrutiny in more recent years with more refined estimates of the emissions footprint of the natural gas supply chain[32].

The IEA said in its May 2021 roadmap for reaching net-zero global emissions by 2050 that "no new natural gas fields are needed [in the net-zero scenario] beyond those already under development" and that "also not needed are many of the liquefied natural gas … facilities currently under construction or at the planning stage," with the LNG trade declining by 60% from 2020 in the agency's scenario[33].

Rising Concern Over Lifecycle Emissions

In November 2021, parties to the Paris Agreement on climate change reaffirmed their commitment to "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C" in order to avoid the most catastrophic consequences of climate change.[34] An emphasis on mitigating

[31] IEA. (2019, July). *The role of gas in today's energy transitions*. International Energy Agency. Retrieved from https://www.iea.org/reports/the-role-of-gas-in-todays-energy-transitions.

[33] IEA. (2021, May). *Net Zero by 2050: A Roadmap for the Global Energy Sector*. Retrieved from https://www.iea.org/reports/net-zero-by-2050.

[34] IPCC (2021). Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson- Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press.

emissions of methane also emerged from the summit, with the White House promoting a Global Methane Pledge, which targets a 30% reduction of worldwide emissions of methane by 2030[35].

Methane has a more potent warming effect than CO_2, with a 100-year global warming potential that is up to 34 times greater and a 20-year warming potential that is up to 86 times greater. Methane remains the second-biggest contributor to climate change among anthropogenic sources of emissions, but it remains in the atmosphere for a shorter time period than CO_2. Methane has an atmospheric lifetime of about 9 years[36], while CO_2, which is produced by the combustion of natural gas, can last for hundreds of years. Emissions of both greenhouse gases are sources of major concern in terms of mitigating climate change. However, methane in particular has come under sharper focus in recent years in part because of the lack of common technological methods for measuring and reporting methane emissions, which makes it difficult to define the scope of the emissions and opportunities for abating them[37].

The oil and gas sector is one of the main sources of methane emissions in the U.S. and a key target for regulatory controls, with U.S. Environmental Protection Agency (EPA) estimating

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[35] POTUS. (2021, November 2). *Fact sheet: President Biden tackles methane emissions, Spurs innovations, and supports sustainable agriculture to build a clean energy economy and create jobs*. The White House. Retrieved from https://www.whitehouse.gov/briefing-room/statements-releases/2021/11/02/fact-sheet-president-biden-tackles-methane-emissions-spurs-innovations-and-supports-sustainable-agriculture-to-build-a-clean-energy-economy-and-create-jobs/.

[36] NOAA. (2021). *Measuring & Analyzing Greenhouse Gases: Behind the Scenes*. US Department of Commerce. Retrieved November 25, 2021, from https://gml.noaa.gov/outreach/behind_the_scenes/gases.html#:~:text=On%20average%2C%20each%20molecule%20of,gas%20contribution%20to%20radiative%20forcing.

[37] UNECE. (2021). *Methane Management*. United Nations Economic Commission for Europe. Retrieved November 28, 2021, from https://unece.org/challenge.

about 197 million tonnes of methane emitted by the sector in 2019, for about 30% of the country's methane emissions[38].

Studies in recent years have repeatedly provided evidence that official greenhouse gas inventory estimates undercount emissions from the oil and gas sector. A 2018 study published in *Science* found that 2015 U.S. oil and natural gas supply chain emissions were 60% higher than the EPA inventories reflected, an estimate derived from modeling based on ground-level measurements and aircraft observations[39]. Researchers concluded that the gap in the EPA inventory was likely a result of the official estimate missing emissions released during "abnormal operating conditions" such as equipment malfunctions that bottom-up engineering emissions estimates assuming normal operations fail to capture when they are reported to the EPA[40].

Another August 2021 research paper published in *Nature Communications* cited a recent synthesis of field measurements of methane at different spatial scales that were up to 2 times greater than official estimates, with the production segment of the supply chain the main contributor[41].

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[38] EPA. (2021, April 28). *Estimates of Methane Emissions by Segment in the United States*. EPA. Retrieved from https://www.epa.gov/natural-gas-star-program/estimates-methane-emissions-segment-united-states.

[39] Alvarez, R. A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., Davis, K. J., Herndon, S. C., Jacob, D. J., Karion, A., Kort, E. A., Lamb, B. K., Lauvaux, T., Maasakkers, J. D., Marchese, A. J., Omara, M., Pacala, S. W., Peischl, J., Robinson, A. L., … Hamburg, S. P. (2018, July 13). *Assessment of methane emissions from the U.S. oil and gas supply chain*. Science. Retrieved November 30, 2021, from https://www.science.org/doi/pdf/10.1126/science.aar7204.

[40] Ibid.

41 Rutherford, J. S., Sherwin, E. D., Ravikumar, A. P., Heath, G. A., Englander, J., Cooley, D., Lyon, D., Omara, M., Langfitt, Q., & Brandt, A. R. (2021, August 5). Closing the methane gap in US oil and natural gas production emissions inventories. Nature Communications. Retrieved December 4, 2021, from https://www.nature.com/articles/s41467-021-25017-4.

Such findings have fueled the growing pressure from investors and buyers in end-user markets on U.S. LNG exporters to reduce supply chain emissions. This pressure has been particularly strong among European customers, with many major LNG portfolio traders such as Royal Dutch Shell, Trafigura, Vitol, and Gunvor based in Europe[42].

Some industry officials interpreted a November 2020 decision[43] by the French multinational utility Engie to halt talks over a long-term contract for LNG supplies linked to the proposed Rio Grande LNG export terminal in South Texas as a warning shot that U.S. LNG exports could suffer from concerns over supply chain emissions, particularly of methane[44]. Within months, the leading U.S. LNG trade group announced[45] the adoption of new principles focused on increasing voluntary efforts to reduce emissions such as by improving data quality and to support "well-designed" government policies that help reduce emissions throughout the supply chain[46]. However, members stopped short of a commitment to enforce any specific desired outcomes of suppliers and shippers for reducing supply chain emissions. Such a commitment could strongly influence on U.S. oil and gas producers and midstream companies given the previously discussed Platts projection about LNG's growing influence on domestic gas production. Cheniere by itself on some days is the single largest physical buyer of natural gas in

[42] Paul, C., & Weber, M. (2021, June 9). *Natural gas in transition: Emissions-conscious markets weigh on US LNG'S Future*. S&P Global Market Intelligence. Retrieved August 15, 2021, from https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/natural-gas-in-transition-emissions-conscious-markets-weigh-on-us-lng-s-future-64822177.

[43] Eaton, C., & McFarlane, S. (2020, November 3). *France's Engie backs out of U.S. LNG deal*. The Wall Street Journal. Retrieved December 4, 2021, from https://www.wsj.com/articles/frances-engie-backs-out-of-u-s-lng-deal-11604435609#.

[44] Paul, C. (2021, January 25). *US LNG industry adopts principles to curb methane emissions*. S&P Global Market Intelligence. Retrieved December 4, 2021, from https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/us-lng-industry-adopts-principles-to-curb-methane-emissions-62276818.

[45] Ibid.

[46] CLNG. (2021, January 25). *Center for LNG Announces Methane Principles*. Retrieved from https://www.lngfacts.org/wp-content/uploads/sites/2/2021/01/CLNG-Methane-Principles-FLYER-Final.pdf.

the U.S., but it is difficult to gauge the potential of the company or the broader U.S. LNG sector to assert its market power to demand emission reductions and how such a move could affect prices of U.S. natural gas that they use to produce their product.

In the months following the Engie-Rio Grande development, multiple U.S. LNG producers including Cheniere[47], Venture Global[48], and Rio Grande LNG developer NextDecade Corp.[49] said they were considering investments in carbon capture and storage projects, although none have released detailed information about the underlying economics of potential projects, likely due to competitive reasons.

NextDecade, for example, said when it announced its intent to purchase a carbon capture and storage project in March 2021 that the venture would have an "all-in" cost of $63/tonne to $74/tonne of CO2 "before any benefit" from existing[50] federal Section 45Q tax credits that incentivize carbon capture projects[51]. But the company has not made public a breakdown of that cost estimate, including whether the projections assume sales of captured carbon for enhanced oil recovery operations, which could undermine its impact in terms of mitigating emissions.

Qatar Petroleum, the world's largest LNG exporter, has upped the pressure on U.S. developers with the announcement that it would include carbon capture and storage technologies

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[47] Cheniere. (2021, June). *Built for the Challenge: 2020 Corporate Responsibility Report*. Retrieved from https://www.cheniere.com/pdf/Cheniere_CR_report.pdf.

[48] Venture Global. (2021, May 27). *Venture Global Launches Carbon Capture and Sequestration Project*. Venture Global LNG. Retrieved December 4, 2021, from https://venturegloballng.com/press/venture-global-launches-carbon-capture-and-sequestration-project/.

[49] NextDecade. (2021, March 18). *NextDecade launches next Carbon Solutions*. NextDecade Corp. Retrieved December 4, 2021, from http://investors.next-decade.com/news-releases/news-release-details/nextdecade-launches-next-carbon-solutions.

[50] CRS. (2021, June 8). *The Tax Credit for Carbon Sequestration (Section 45Q)*. Congressional Research Service. Retrieved from https://sgp.fas.org/crs/misc/IF11455.pdf.

[51] Ibid.

on a 33-million-tonne-per annum (mtpa) LNG capacity expansion of its North Field East export operations, which the export giant commercially sanctioned[52] in February 2021. The project would initially include 2.1 mtpa of CO2 capture with a goal of expanding capture capacity to 7 mtpa by the end of the decade, but the Qataris have also said expansions will focus on enhanced oil recovery, which has above-mentioned implications for carbon intensity[53].

Cheniere, the largest U.S. LNG exporter with 45 mtpa of LNG production capacity upon the completion of train 6, has responded to the emissions concerns of its customers and investors by rolling out a series of climate initiatives in 2021, including the publication of its first annual climate-risk assessment[54] and a pledge to provide customers with emissions data for each cargo it exports beginning in 2022[55]. Cheniere said at the time of its Feb. 24, 2021 announcement of the "cargo emissions tags," or "CE Tags" that it would initially use a proprietary lifecycle analysis model built on accounting frameworks created by the U.S. Department of Energy's National Energy Technology Laboratory. In addition, the analysis would initially include publicly available data from value chain participants, and operational data from its two liquefaction terminals, including the company's Corpus Christi LNG export facility in Texas. Cheniere would

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[52] QP. (2021, February 10). *Qatargas Issues Letter of Award to Chiyoda Technip Joint Venture For NFE Project*. Retrieved from https://www.qatargas.com/english/MediaCenter/Pages/Press%20Releases/Qatargas-issues-Letter-of-Award-to-Chiyoda-Technip-Joint-Venture-for-NFE-project.aspx?csrt=14938923370326852744.

[53] S&P Global Platts Analytics. (2021, February 24). *Future Energy Outlook: Annual Guidebook 2021* .

[54] Cheniere. (2021, June). *Built for the Challenge: 2020 Corporate Responsibility Report*. Retrieved from https://www.cheniere.com/pdf/Cheniere_CR_report.pdf.

[55] Cheniere. (2021, February 24). *Cheniere to provide cargo emissions data to LNG customers*. Cheniere Energy, Inc. Retrieved from https://lngir.cheniere.com/news-events/press-releases/detail/214/cheniere-to-provide-cargo-emissions-data-to-lng-customers.

work to improve its data “with the ultimate goal of providing dynamic GHG emissions data” [56]. Cheniere has not made its proprietary model or a CE Tag publicly available to date.

The company has also begun participating in peer-reviewed academic studies monitoring and quantifying emissions associated with its exports. In August 2021, researchers published a ACS Sustainable Chemistry & Engineering paper that offered a framework for “supplier specific GHG emission data for LNG from the producing well to regasification at the destination port” [57]. Researchers estimated that greenhouse gas emissions intensities that were 30% to 43% lower than other analyses that had relied on national or regional average emissions profiles, citing gas production, gathering, transmission, and ocean transport segments as the drivers of the difference. But the Cheniere-funded paper’s focus on emissions intensity – a measure of emissions based the amount of fuel used– does not offer a sense of absolute emissions. A pollution rate, when not paired with absolute emissions data, is of limited utility for independently assessing climate impacts or emissions abatement potential.

Instead, in a development central to this research paper, there was another climate-focused initiative by Cheniere – the trade of the company’s first carbon-neutral cargo, announced in May 2021[58]. Cheniere has not disclosed the absolute emissions associated with that trade, which entailed an April cargo delivered to Royal Dutch Shell in Europe and the purchase of

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[56] Ibid.

[57] Roman-White, S. A., Littlefield, J. A., Fleury, K. G., Allen, D. T., Balcombe, P., Konschnik, K. E., Ewing, J., Ross, G. B., & George, F. (2021, August 3). *LNG supply Chains: A Supplier-specific Life-cycle assessment for Improved Emission Accounting.* ACS Sustainable Chemistry & Engineering. https://pubs.acs.org/doi/abs/10.1021/acssuschemeng.1c03307.

[58] Cheniere. (2021, May 4). *Cheniere and Shell collaborate to deliver carbon-neutral US LNG to Europe*. Cheniere Energy Inc. Retrieved from https://lngir.cheniere.com/news-events/press-releases/detail/219/cheniere-and-shell-collaborate-to-deliver-carbon-neutral-us.

carbon credits “retiring” unspecified “nature-based offsets” for estimated CO2 equivalent emissions for lifecycle emissions throughout the supply chain[59].

The Advent of ‘Carbon-Neutral LNG’

Carbon-neutral LNG cargoes do not involve the abatement of emissions in the LNG supply chain. The growing global market for carbon offsets must address well-documented challenges to play a more meaningful role in addressing climate change, including overcoming concerns about transparency associated with offsetting, the permanence of offsets, and additionality,[60] which is the concept of determining whether greenhouse gas reductions would have occurred in the absence of the associated purchase of an offset[61]. This is a problem for the broader world economy, and an exploration of necessary improvements to carbon-offset quality and transparency is beyond the scope of this research paper. But such improvements to the usage and reporting of carbon offsets may be necessary to facilitate so-called green premiums for LNG cargoes marketed by developers competing on the basis of supplies' carbon footprint.

Notably, the trade of carbon-neutral LNG cargoes remains a small part of the overall LNG market with just 14 carbon-neutral cargoes agreed to or delivered globally from the time Royal Dutch Shell announced the first carbon-neutral LNG transaction in June 2019[62] through

[59]Ibid.

[60] Stapczynski, S., Rathi, A., & Marawanyika, G. (2021, August 11). *How to Sell ‘Carbon Neutral’ Fossil Fuel That Doesn’t Exist*. Bloomberg. Retrieved August 15, 2021, from https://www.bloomberg.com/news/features/2021-08-11/the-fictitious-world-of-carbon-neutral-fossil-fuel?sref=DLVyDcXJ.

[61] CORE. (2021). *Carbon Offset Guide: Additionality*. Carbon Offset Research and Education . Retrieved December 7, 2021.

[62] Shell. (2019, June 18). *Tokyo Gas and GS Energy to receive world's first carbon neutral LNG cargoes from Shell*. Royal Dutch Shell. Retrieved December 4, 2021, from https://www.shell.com/business-customers/trading-and-supply/trading/news-and-media-releases/tokyo-gas-and-gs-energy-to-receive-worlds-first-carbon-neutral-lng-cargoes-from-shell.html.

the first six months of 2021[63]. This number should be compared to the 5,000 LNG cargoes being traded worldwide in full-year 2020[64]. However, the burgeoning carbon-neutral LNG market has the potential to grow to become a critical driver for true emissions reduction in the LNG value chain, especially as governments in end-user markets place stricter limits on the carbon footprint of imported goods, according to a July 2021 paper by researchers Erin Blanton, a senior research scholar at Columbia University's Center on Global Energy Policy, and Samer Mosis, who leads LNG analytics at S&P Global Platts[65]. Blanton and Mosis also pointed to the potential for the carbon-neutral LNG trade to aid the development of a better understanding of the carbon footprint of the global LNG trade by incentivizing improvements in monitoring and reporting of supply chain emissions[66].

Market participants including U.S. natural gas producers have expressed hope that buyers of natural gas will begin to pay a premium for cleaner gas supplies in the coming years, with some estimating that natural gas certified as "responsibly produced" with fewer emissions than competing supplies could get up to 5% above market prices, or about 15 cents per mcf[67].

Blanton and Mosis identified a series of developments that could help foster a "robust and trusted" carbon-neutral LNG market, including an independent organization being given a mandate to create global standards for measuring and reporting of LNG supply chain emissions and offsets; greater disclosure by buyers and sellers of any "green" premiums associated with the

[63] Blanton, E. M., & Mosis, S. (2021, July 8). The Carbon-Neutral LNG Market: Creating a Framework for Real Emissions Reductions. Columbia University's Center on Global Energy Policy. Retrieved August 15, 2021, from https://www.energypolicy.columbia.edu/research/commentary/carbon-neutral-lng-market-creating-framework-real-emissions-reductions.

[64] Ibid.

[65] Ibid.

[66] Ibid.

[67] Hampton, L., & DiSavino, S. (2021, June 30). *U.S. natgas producers hope customers will pay more for 'green gas'*. Reuters. Retrieved December 3, 2021, from https://www.reuters.com/article/us-usa-naturalgas-transition-focus-idTRNIKCN2E60F3.

trades; and annual third-party verification of offsets[68]. The researchers also argued that the relative uncertainty about well-to-tank emissions compared to downstream emissions that occur at the point of combustion should not preclude the growth of carbon-neutral LNG trading[69]. Well-to-tank emissions refer to emissions along the value chain from the point of upstream production through transportation to the LNG facility, the liquefaction process, and oceanic transport, ending once cargo is delivered and regasified, making the fuel supply no longer any different from the fuel in its gaseous form.

On Nov. 17, 2021, the Paris-based nonprofit organization the International Group of Liquefied Natural Gas Importers (GIIGNL) published a framework for carbon-neutral LNG cargoes, designed to "provide a common source of best practice principles in the monitoring, reporting, reduction, offsetting and verification, of GHG emissions associated with a delivered cargo of LNG," from the point of natural gas production to end use[70]. The group, which represents nearly all of the companies globally that are active in the import and regasification of LNG, urged the industry to move away from the commonly used "carbon-neutral LNG" as buyers and sellers when trading cargoes[71]. Instead, GIIGNL encouraged using terms such as "GHG neutral" and "GHG offset" to describe cargo attribution inline with the recommended framework to promote accuracy and emphasize the importance of methane emissions[72]. GIIGNL stopped short of developing a certification process that could be applied to traded cargoes and

[68] Blanton, E. M., & Mosis, S. (2021, July 8). The Carbon-Neutral LNG Market: Creating a Framework for Real Emissions Reductions. Columbia University's Center on Global Energy Policy. Retrieved August 15, 2021, from https://www.energypolicy.columbia.edu/research/commentary/carbon-neutral-lng-market-creating-framework-real-emissions-reductions.

[69] Ibid.

[70] GIIGNL. (2021, November 17). *MRV and GHG Neutral LNG Framework*. International Group of Liquefied Natural Gas Importers. Retrieved November 26, 2021, from https://giignl.org/framework/.

[71] Ibid

[72] Ibid.

said the framework was designed to support existing emissions standards and methodologies governing GHG emissions calculations rather than replace them[73]. The organization encouraged parties reporting emissions to implement emissions-reduction plans and limit the use of offsets to the residual emissions that cannot be abated[74].

GIIGNL said that cargoes described as “GHG Neutral” should clear a high bar that includes a commitment to long-term decarbonization and aligns an internationally accepted standard for carbon neutrality provided currently by the PAS 2060:2014, which the British Standards Institution publishes[75]. Crucially, the framework prioritized site-specific data, the reporting of absolute emissions and emissions intensities, specific breakdowns of lifecycle stages and volumes of specific greenhouse gases emitted, all of which should be independently verified to maintain credibility[76]. It also identified transparency as critical and advised reporters of LNG cargoes to clearly explain the use of estimates for any stage of emissions[77].

A review of GIIGNL’s framework makes clear that the LNG sector has a long way to go. It is well understood that vast majority of emissions associated with LNG occur at end use, which accounts for about 70% of full lifecycle greenhouse emissions when the gas is combusted for electricity generation[78]. Well-to-tank emissions are less well understood, as supply chain

[73] Ibid.
[74] Ibid.
[75] Ibid.
[76] Ibid.
[77] Ibid.
[78] Ibid.

emissions are a long-running cause for uncertainty about the carbon footprint of U.S. natural gas supplies in particular[79].

Blanton and Mosis found that the early trade of carbon neutral LNG cargoes have focused on well-to-tank emissions, suggesting the emergence of a structure where suppliers take responsibility for well-to-tank emissions, while buyers take financial responsibility for emissions associated with end use of the fuel[80]. Until better measurements are available for customized data on absolute emissions, Blanton and Mosis recommended that trading parties follow guidance developed by the U.K. Department of Business, Energy, and Industrial Strategy (BEIS) as a "solid foundation" for estimating supply chain emissions that many carbon-neutral trades have used.[81]

Blanton and Mosis cite data[82] from the company Sphera underpinning the BEIS estimate to offer a breakdown of commonly accepted emissions estimates for different stages of the LNG supply chain well-to-tank emissions, shown in fig. 5. About 50% of the well-tank-emissions are attributed to upstream gas production, processing, and transport; about 33% is attributed to the

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[79] Venkatesh, A., Jaramillo, P., Griffin, W. M., & Matthews, H. S. (2011, August 16). *Uncertainty in Life Cycle Greenhouse Gas Emissions from United States Natural Gas End-Uses and its Effects on Policy*. Environmental Science & Technology. Retrieved December 5, 2021, from https://pubs.acs.org/doi/abs/10.1021/es200930h.

[80] Blanton, E. M., & Mosis, S. (2021, July 8). *The Carbon-Neutral LNG Market: Creating a Framework for Real Emissions Reductions*. Columbia University's Center on Global Energy Policy. Retrieved August 15, 2021, from https://www.energypolicy.columbia.edu/research/commentary/carbon-neutral-lng-market-creating-framework-real-emissions-reductions.

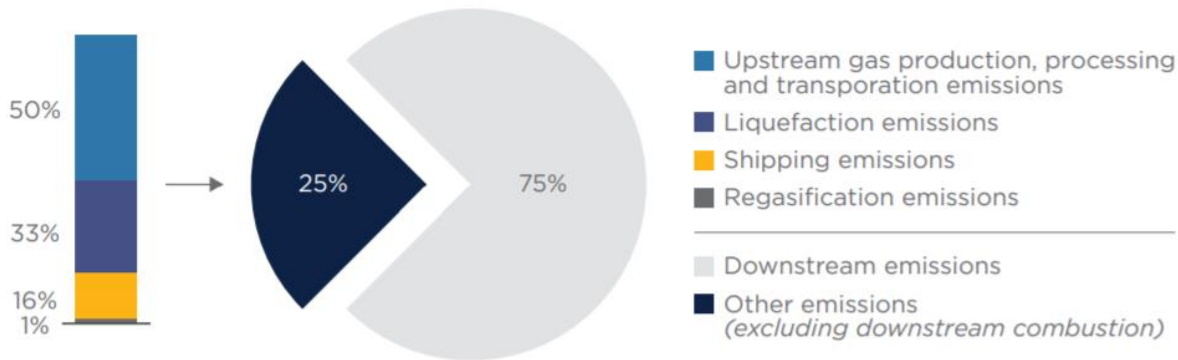
[81] Ibid.

[82] Sphera. (2020, July 8). *GHG intensity of Natural Gas Transport*. Sphera. Retrieved November 26, 2021, from https://sphera.com/research/ghg-intensity-of-natural-gas-transport/.

facility-level emissions; about 16% of emissions are attributed to oceanic transport of LNG; and about 1% are attributed to regasification[83].

[83] Blanton, E. M., & Mosis, S. (2021, July 8). *The Carbon-Neutral LNG Market: Creating a Framework for Real Emissions Reductions*. Columbia University's Center on Global Energy Policy. Retrieved August 15, 2021, from https://www.energypolicy.columbia.edu/research/commentary/carbon-neutral-lng-market-creating-framework-real-emissions-reductions.

Figure 5: Blanton and Mosis Breakdown Well-to Tank Emissions[84]



Source: Breakdown of "other emissions" (excluding downstream) from "GHG Intensity of Natural Gas Transport," Sphera, July 8, 2020, https://sphera.com/research/ghg-intensity-of-natural-gas-transport/; breakdown of downstream versus other emissions from "Greenhouse gas reporting: conversion factors 2020," UK Department for Environment, Food and Rural Affairs, updated July 17, 2020, https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020.

A series of satellite monitoring projects expected to start returning methane emissions data in the coming years like the Environmental Defense Fund's MethaneSAT project, which is scheduled to launch in 2022, stand to increase the scrutiny on the U.S. oil and gas sector in the coming years by investors and policymakers by offering a more accurate picture of emissions[85]. Market observers from the IEA and Columbia University's Center on Global Energy Policy[86] have also said that satellite monitoring could lead to a disproportionate amount of scrutiny on U.S. emissions for mostly technical reasons, such as difficulty detecting emissions from off-shore production or in snow-covered regions with a high albedo, cautioning that this could result

[84] Ibid.

[85] Elkind, J., Blanton, E. M., van der Gon, H. D., Kleinberg, R., & Leemhuis, A. (2020, October 14). *Nowhere to Hide: Implications for Policy, Industry, and Finance of Satellite-Based Methane Detection*. Columbia University's Center on Global Energy Policy. Retrieved November 30, 2021, from https://www.energypolicy.columbia.edu/research/commentary/nowhere-hide-implications-policy-industry-and-finance-satellite-based-methane-detection.

[86] Ibid.

in a competitive disadvantage for U.S. LNG over time if methane emissions are not brought under control[87]. This underscores the urgency for the industry to take prompt action to mitigate emissions.

The actions of Cheniere could be of significant influence for the LNG industry and the broader U.S. gas system, with the company expecting to purchase around 7% to 8% of total U.S. gas production on any given day to supply its two export plants which have a total 45 million tonnes per year of capacity with addition of the sixth train at Sabine Pass.[88] Cheniere's level of production capacity makes the company the world's second-largest LNG supplier behind Qatar Petroleum.

Cheniere's Chief Commercial Officer Anatol Feygin said to S&P Global Market Intelligence in a June 2021 news media interview that market forces would answer the question of whether accounting for greenhouse gas emissions associated with the would be widely adopted by the LNG sector and standardized amid the growing competition to market the greenest supplies[89]. Feygin predicted that if there is a lack of transparency about emissions estimated byLNG exporters, the market will use some kind of estimate as a baseline. Feygin said that "in the not-too-distant future, we are going to find ourselves in the place where projects that

[87] Paul, C. (2021, June 22). *'If not us, who?' Cheniere leans into cleaning up natural gas supply chain*. S&P Global Market Intelligence. Retrieved December 5, 2021, from https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/if-not-us-who-cheniere-leans-into-cleaning-up-natural-gas-supply-chain-65118193.

[88] Ibid.

[89] Ibid.

are better than that model will suggest will be transparent, and projects that are worse will be handicapped by the fact that they are assumed to be the modeled-number at best"[90].

Cheniere does not pay a premium for cleaner natural gas supplies that it purchases for liquefaction and has not developed a methodology for rating producers[91]. The company has promoted voluntary emissions-reduction efforts among its suppliers and reported that 70% of its 2020 gas purchases were from companies with a voluntary methane emissions reduction target[92].

In June 2021, Cheniere announced a collaboration with five natural gas producers and academic institutions to quantify, monitor, report, and verify emissions associated with those operations in order to develop a baseline emissions level for its supplies[93].

Recognizing the urgency for mitigating emissions from the U.S. LNG supply chain while such efforts are underway, this research paper offers its own baseline for Cheniere's Sabine Pass and the broader U.S. LNG sector, following the BEIS guidance favored by Blanton and Mosis and utilized in Cheniere's carbon-neutral trade with Royal Dutch Shell announced in May 2021. This research then turns to carbon capture and storage as a prime opportunity for reducing facility-level emissions because these emissions occur at the stage of the LNG supply chain that LNG exporters have the most direct influence over abating. In this paper, Sabine Pass is used as

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[90] Ibid.

[91] Hampton, L., & DiSavino, S. (2021, June 30). *U.S. natgas producers hope customers will pay more for 'green gas'*. Reuters. Retrieved December 3, 2021, from https://www.reuters.com/article/us-usa-naturalgas-transition-focus-idTRNIKCN2E60F3.

[92] Cheniere. (2021, June). *Built for the Challenge: 2020 Corporate Responsibility Report*. Retrieved from https://www.cheniere.com/pdf/Cheniere_CR_report.pdf.

[93] Cheniere. (2021, June 10). *Cheniere Announces Collaboration with Natural Gas Suppliers and Academic Institutions to Quantify, Monitor, Report and Verify GHG Emissions*. Cheniere Energy, Inc. Retrieved from https://lngir.cheniere.com/news-events/press-releases/detail/220/cheniere-announces-collaboration-with-natural-gas-suppliers.

the case study. Finally, this paper analyzes potential costs of deploying carbon-capture-and-storage at Sabine Pass and the potential economics of doing so.

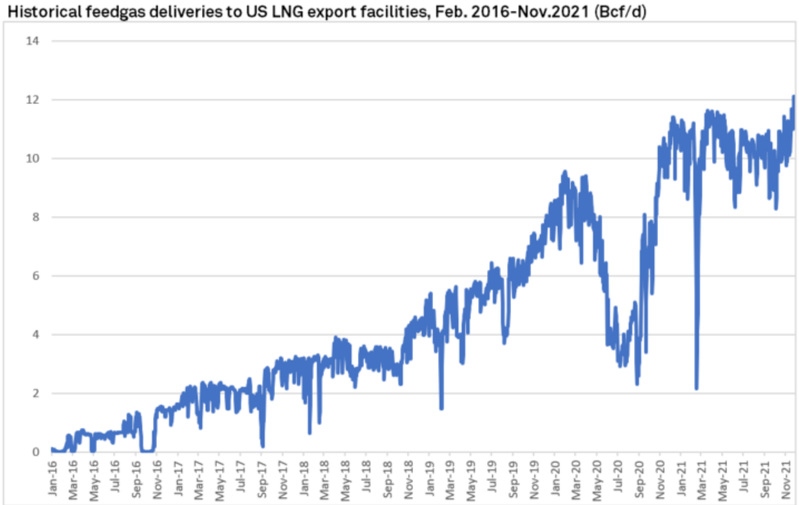
Methodology, Results and Analysis

This research takes the BEIS emissions conversion factor and applies it to S&P Global Market Intelligence and S&P Global Platts data showing daily feedgas deliveries to U.S. LNG terminals going back to the start of exports from the Lower 48 in 2016. This data is compiled from daily, publicly available capacity postings that U.S. pipeline companies make. Total flows in 2019 are used as a basecase to reflect normal activity outside of the upheaval in the global gas market starting in April 2020 and lasting for months as more than 170 U.S. LNG cargoes were canceled, causing a months-long crash in feedgas deliveries to U.S. LNG export facilities as total facility utilization dropped to as low as under 30%[94]. Because 2021 is ongoing at this writing, calculations of 2021 emissions assume average total flows in November 2021 of about 11.4 dekatherms per day (Dth/d) to the six major U.S. LNG terminals in operation continue through December 2021, shown in fig. 6. Total gas deliveries to Sabine Pass averaged approximately 4.3 Dth/d in November 2021, as shown in fig. 8. Utilizing 2021 emissions is useful because it captures some of the feedgas demand at Sabine Pass during the commissioning work of train six, but it is acknowledged that annual emissions from the facility could be higher once the train entered into full commercial service.

[94] S&P Global Platts Analytics. (2021, February 24). *Future Energy Outlook: Annual Guidebook 2021*

Figure 6:

Historical feedgas deliveries to US LNG export facilities, Feb. 2016-Nov.2021 (Bcf/d)

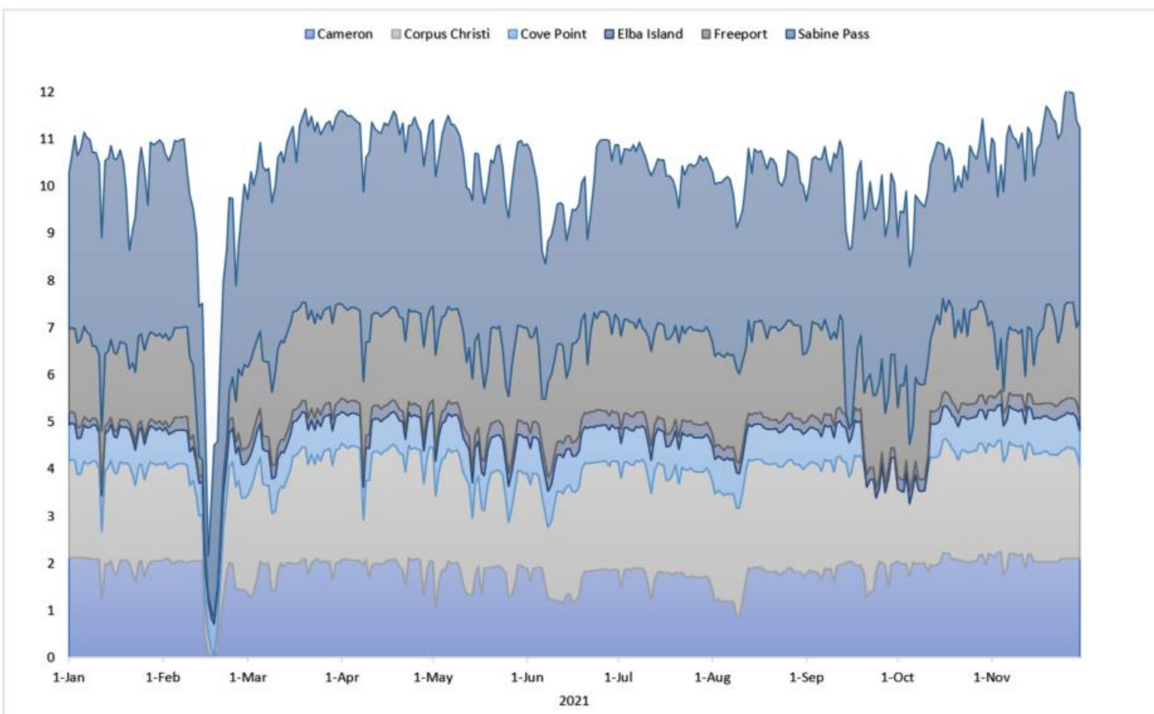


Data compiled Dec. 1, 2021.

Sources: S&P Global Market Intelligence; S&P Global Platts

Figure 7:

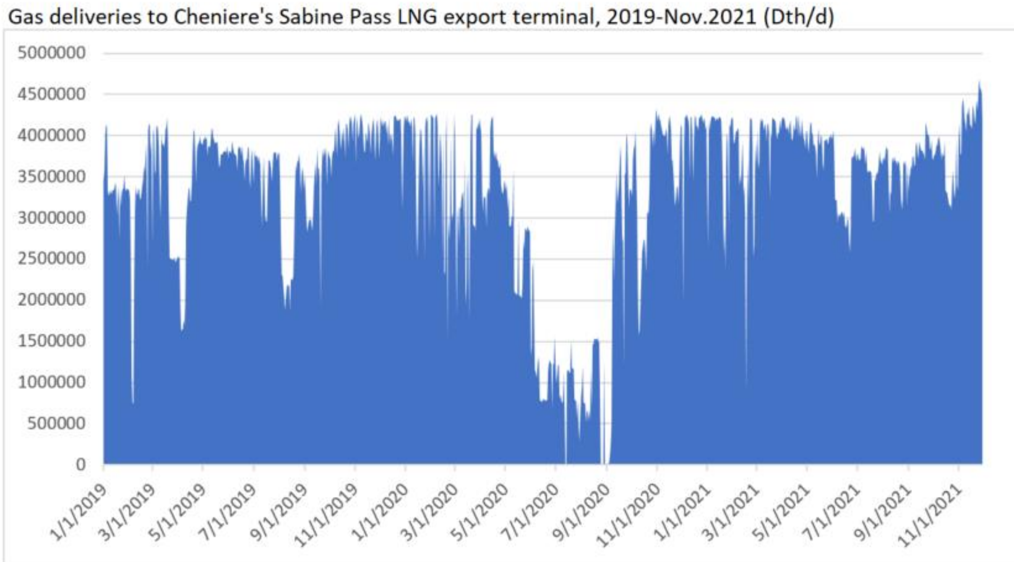
Daily gas deliveries to US LNG export facilities by facility, 2021 (Bcf/d)



Data compiled Dec. 1, 2021.

Source: S&P Global Market Intelligence

Figure 8:



Data compiled Dec. 1, 2021.

Sources: S&P Global Market Intelligence; S&P Global Platts; U.K. BEIS

BEIS uses the Sphera study, which follows the International Organization for Standardization's ISO 15050 protocol to estimate that well-to-tank emissions for LNG imported to the U.K. equate to about 0.88 tonnes of CO2 equivalent per metric tonne of LNG[95]. By comparison, BEIS provides for downstream combustion of LNG an estimate of about 2.76 tonnes of CO2e emissions per tonne of LNG[96]. Feedgas deliveries are converted to tonnes by converting daily flows measured in dekatherms, using S&P Global Platts conversion factors, as shown in fig. 9 and fig. 11. A therm is about equal to a British thermal unit, or Btu, and 52 MMBtu are assumed per tonne of LNG.

[95] BEIS. (2020, June 9). Government Emission Conversion Factors for Company Greenhouse Gas Reporting: Conversion Factors 2020. Retrieved December 5, 2021, from https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020.

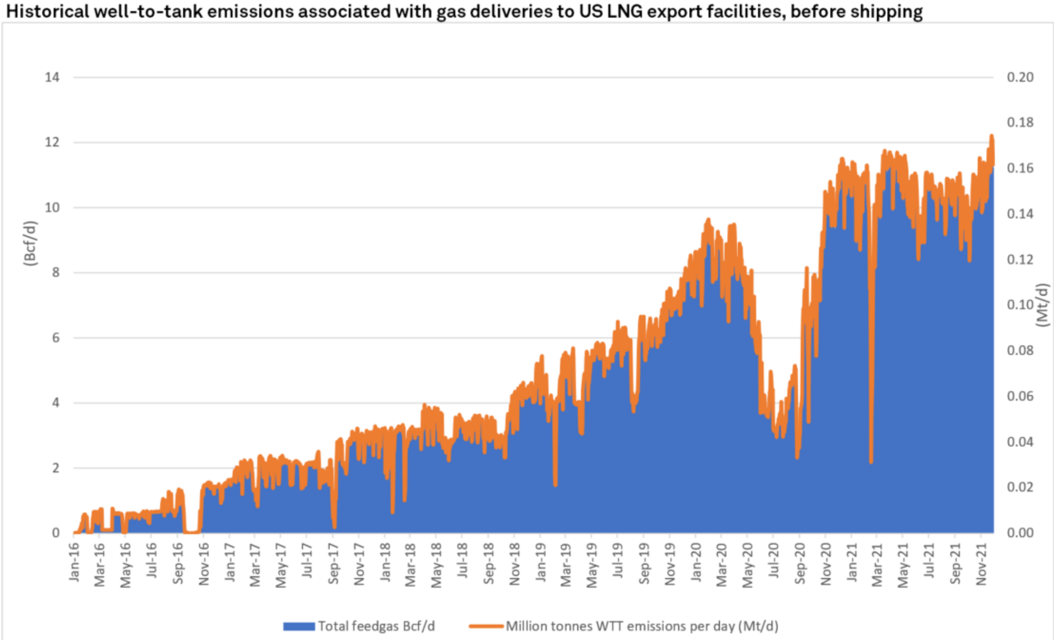
[96] Ibid.

Supply-chain emissions before shipping are calculated by subtracting 17% from the well-to-tank total to cover share of emissions from oceanic transport to the U.K. and emissions from regasification estimated in the BEIS framework[97] based on the Sphera study[98], as shown in fig. 10.

Sabine Pass facility-level emissions are assumed to be 33% of the well-to-tank emissions after shipping using the BEIS framework illustrated in the previous section by Blanton and Mosis, and as shown in fig. 11 and fig. 12.

Figure 9:

Historical well-to-tank emissions associated with gas deliveries to US LNG export facilities, before shipping



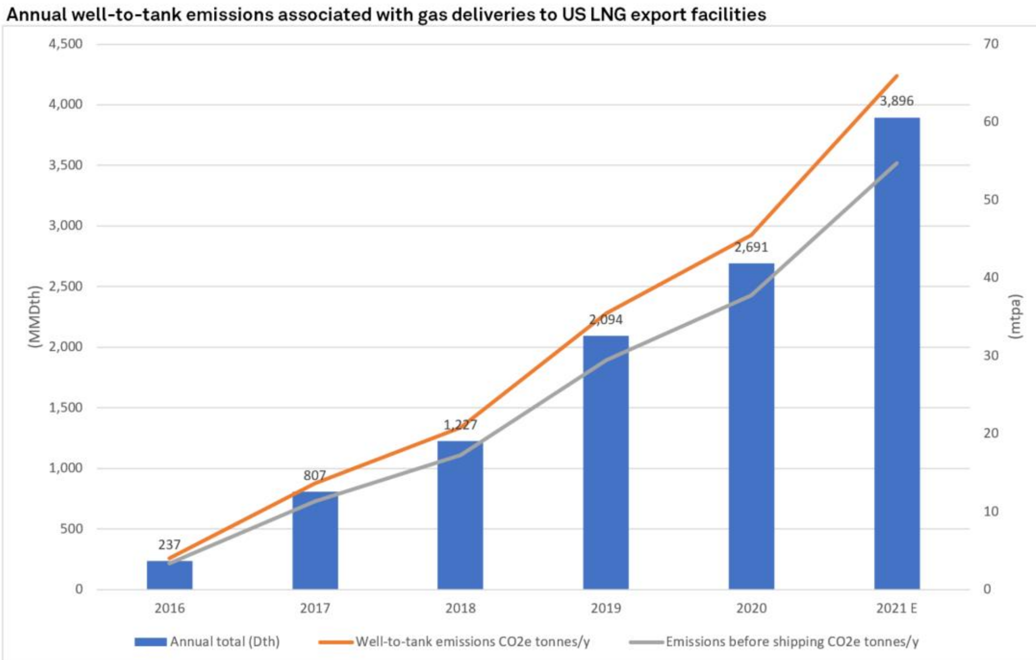
Data compiled Dec. 1, 2021.

Sources: S&P Global Market Intelligence; S&P Global Platts; U.K. BEIS

[97] Blanton, E. M., & Mosis, S. (2021, July 8). *The Carbon-Neutral LNG Market: Creating a Framework for Real Emissions Reductions*. Columbia University's Center on Global Energy Policy. Retrieved August 15, 2021, from https://www.energypolicy.columbia.edu/research/commentary/carbon-neutral-lng-market-creating-framework-real-emissions-reductions

[98] Sphera. (2020, July 8). *GHG intensity of Natural Gas Transport*. Sphera. Retrieved November 26, 2021, from https://sphera.com/research/ghg-intensity-of-natural-gas-transport/.

Figure 10:

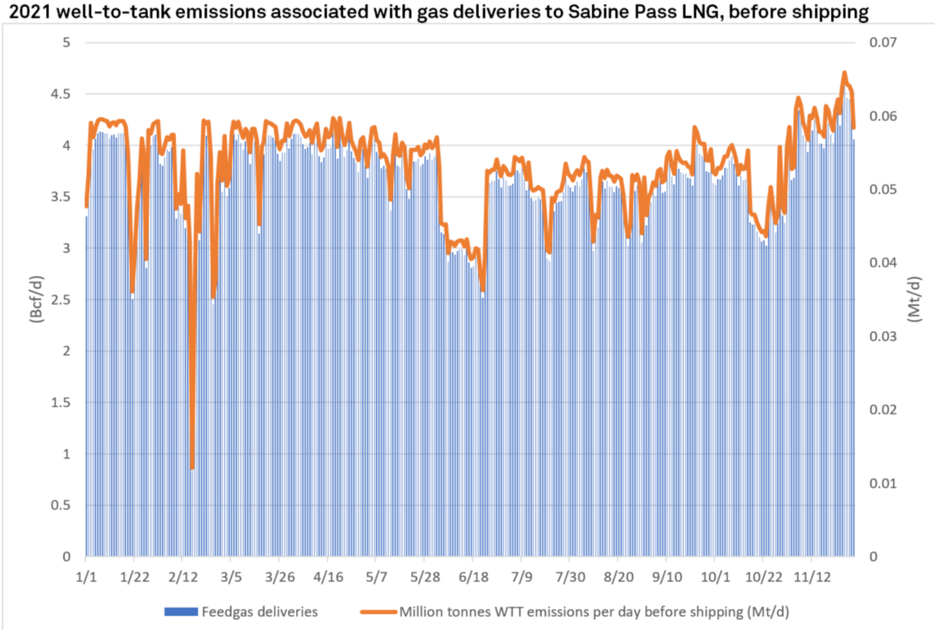


Data compiled Dec. 1, 2021.

Sources: S&P Global Market Intelligence; S&P Global Platts; U.K. BEIS

Figure 11:

2021 well-to-tank emissions associated with gas deliveries to Sabine Pass LNG, before shipping

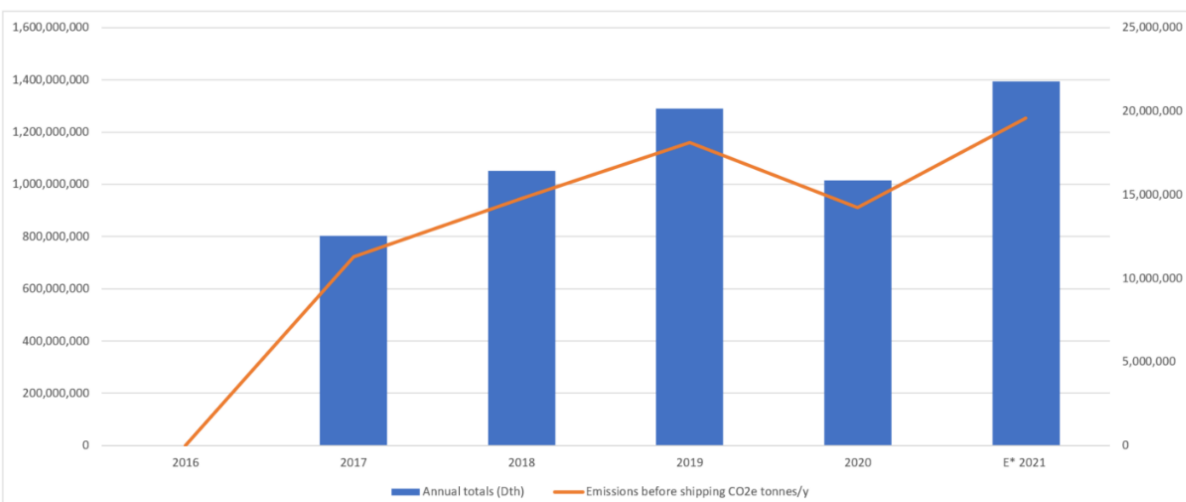


Data compiled Dec. 1, 2021.

Sources: S&P Global Market Intelligence; S&P Global Platts; U.K. BEIS

Figure 12:

Annual well-to-tank emissions associated with gas deliveries to Cheniere's Sabine Pass LNG export terminal, before shipping



Data compiled Dec. 1, 2021.

Sources: S&P Global Market Intelligence; S&P Global Platts; U.K. BEIS

*Average November 2021 flows used to estimate December 2021 deliveries

Results

Using the BEIS framework for well-to-tank analysis, the total well-to-tank emissions from the LNG sector are estimated to range from more than 35 million tonnes CO2e in 2019 to nearly 66 million tonnes CO2e in 2021. This estimate is based on total annual gas deliveries ranging from nearly 2.1 billion Dth in 2019 to nearly 3.9 billion Dth in 2021. When shipping and regasification emissions are removed, supply chain emissions from the wellhead to the point of export range from about 29.4 million tonnes CO2e to about 54.7 million tonnes CO2e, as shown in fig. 10. The size of this increase in emissions from 2019 to 2021 is unsurprising considering that the U.S. LNG production capacity has almost doubled across this period as newly completed liquefaction facilities came online[99].

Sabine Pass is estimated to account for a significant portion of these emissions, with 2019 well-to tank emissions ranging from more than 21.8 million tonnes CO2e in 2019 to nearly 23.6 million tonnes CO2e in 2021 and shown on fig. 12. These volumes are based on annual flows ranging from nearly 1.3 billion Dth to almost 1.4 billion Dth across the same period. When shipping and regasification emissions are removed, the estimated supply chain emissions associated with Sabine Pass range from more than 18.1 million tonnes CO2e to nearly 19.6 million tonnes, respectively. Facility-level emissions representing 33% of total well-to-tank emissions range from about 7.2 million tonnes CO2e to about 7.8 million tonnes CO2e.

[99] EIA. (2021, November 28). *How much carbon dioxide is produced when different fuels are burned?* U.S. Energy Information Administration. Retrieved from https://www.eia.gov/tools/faqs/faq.php?id=73&t=1.

Notably, the 2019 estimate reflects much greater emissions than what Cheniere's master-limited partnership Cheniere Energy Partners that owns and operates Sabine Pass estimated to U.S. regulators. Cheniere Energy Partners reported nearly 5.1 million tonnes CO2e to the U.S. Environmental Protection Agency for 2019 in compliance with the agency's Greenhouse Gas Reporting Program, which requires about 8,000 large emitters to report their annual emissions[100].

Based on the previously discussed research[101] studies showing gaps between official greenhouse gas inventory estimates and observed emissions by the oil and gas sector, the difference between the estimate that this paper offers for Sabine Pass in 2019 and the estimate that Cheniere reported to the EPA for 2019 is likely attributable to "abnormal operating conditions" such as equipment malfunctions, unplanned maintenance, or weather events.

Results: Carbon Capture Analysis

Emissions estimates aid in an analysis of the potential deployment of carbon capture at Sabine Pass. This research also draws on a 2019 techno-economic evaluation of carbon capture potential at LNG facilities by published by the IEA[103]. The IEA study offers a cost estimate for carbon capture at U.S. Gulf Coast LNG facilities at the U.S.-dollar equivalent of $669 million per train, based on a train with a similar sized nameplate capacity to those at Sabine Pass, for a

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[100] EPA. (2020). *2019 Emissions Data reported for Sabine Pass*. EPA. Retrieved October 1, 2021, from https://ghgdata.epa.gov/ghgp/service/facilityDetail/2019?id=1002259&ds=E&et=&popup=true.

[101] Alvarez, R. A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., Davis, K. J., Herndon, S. C., Jacob, D. J., Karion, A., Kort, E. A., Lamb, B. K., Lauvaux, T., Maasakkers, J. D., Marchese, A. J., Omara, M., Pacala, S. W., Peischl, J., Robinson, A. L., … Hamburg, S. P. (2018, July 13). *Assessment of methane emissions from the U.S. oil and gas supply chain*. Science. Retrieved November 30, 2021, from https://www.science.org/doi/pdf/10.1126/science.aar7204.

[103] IEAGHG. (2019, October). *2019-07 techno-economic evaluation of CO2 capture in LNG Plants Projects*. Retrieved November 26, 2021, from https://ieaghg.org/publications/technical-reports/reports-list/9-technical-reports/943-2019-07-techno-economic-evaluation-of-co2-capture-in-lng-plants-projects.

total capital cost of more than $4 billion when calculating costs for all six trains[104]. Each Cheniere train across the company's two export terminals was designed to produce about 4.5 million tonnes of LNG per year but have been uprated with the approval of U.S. federal energy regulators to produce about 5 million tonnes per year – a capacity increase achieved without the construction of any new infrastructure but instead through operational efficiencies such as reductions in production downtime through planned maintenance schedules[105]. As such, the capacity uprating at Sabine Pass should not alter the cost of installing carbon capture facilities because there is no change to the infrastructure on site associated with the uprating.

Cheniere CEO Jack Fusco said in May 2021 that "CCS is important; our initial blush is that it looks very promising at our facilities"[106]. During an August 2021 earnings call, Fusco told investors that the facility's location appears geologically suited for sequestration, but the executive described existing 45Q tax credits as insufficient to make post-combustion carbon capture and sequestration economic, saying "it's not going to work"[107].

To date, Cheniere has not made public any cost estimates, such as a projected cost per tonne of CO2 for capture and storage from emissions at either of its facilities. Cheniere's Senior Director for Climate and Sustainability Fiji George declined to provide such an estimate during an October 2021 forum hosted by the Johns Hopkins School of Advanced International Studies,

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[104] Ibid.

[105] FERC. (2021, October 21). *Order Amending Authorization Under Section 3 of the Natural Gas Act re Sabine Pass Liquefaction, LLC et al under CP19-515.* Elibrary. Retrieved from https://elibrary.ferc.gov/eLibrary/filelist?accession_number=20211021-3032&optimized=false.

[106] Cheniere. (2021, May 5). *Cheniere Energy Partners L P (CQP) Q1 2021 earnings call transcript*. The Motley Fool. Retrieved December 5, 2021, from https://www.fool.com/earnings/call-transcripts/2021/05/05/cheniere-energy-partners-l-p-cqp-q1-2021-earnings/.

[107] Cheniere. (2021, August 5). *Cheniere Energy Inc (LNG) Q2 2021 Earnings Call Transcript*. Motley Fool. Retrieved from https://www.fool.com/earnings/call-transcripts/2021/08/05/cheniere-energy-inc-lng-q2-2021-earnings-call-tran/.

saying the company was not ready to make a public announcement about costs as it evaluates the technology[108]. The Cheniere executive instead recommended recent National Petroleum Council cost data as a source that could provide "a directional idea of the cost of implementation[109]."

This research paper utilizes a cost curve model developed for the National Petroleum Council by Gaffney, Cline & Associates[110]. The Gaffney Cline model returns a $/CO2e estimate for Sabine Pass at a range of about $85/tonne CO2e to about $91/tonne CO2e.

The cash flow projection for Cheniere Energy Partners presented in this research paper uses operational expenditures associated with carbon capture derived from the Gaffney Cline model. In addition, an 85% carbon capture rate is assumed, for a range of more than 6.1 million tonnes CO2 to more than 6.6 million tonnes CO2 of carbon captured based on 2019 and 2021 respective volumes, as shown in fig. 13. The cash flow projection also uses a 2.5% rate for future inflation. The capital cost expenditure estimate used on the cash flow projection is derived from the IEA techno-economic evaluation. Further inputs about Cheniere Energy Partners projected cash flows and expenditures are sourced from consensus estimates of financial analysts reporting on the company[111]. When the IEA-derived plant-cost estimate is used along with the calculations of 2021 and 2019 estimates, respectively[112] 45Q tax credits more than cover the higher operating

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[108] SAIS. (2021, October 27). *Forum on the Greenhouse Gas implications of the Trade of Liquefied Natural Gas*. Retrieved from https://sais.jhu.edu/campus-events?trumbaEmbed=view%3Devent%26eventid%3D538209587.

[109] Ibid.

[110] National Petroleum Council. (2019). *Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage*. National Petroleum Council. Retrieved October 28, 2021, from https://dualchallenge.npc.org/downloads.php.

[111] S&P Capital IQ Pro. (n.d.). *Cheniere Energy Partners L.P., Consensus Estimates*. S&P Capital IQ Pro. Retrieved December 6, 2021, from https://drive.google.com/file/d/1TKIxJarPelyTQNdNkaLcxe1z-wBBtfFe/view?usp=sharing.

[112] Ibid.

expenditures required for capturing greater volumes of CO2e. The output for each case is shown in figure 13.

The cash flow projection, Gaffney Cline modeling results, feedgas delivery data, and well-to-tank emissions calculations can be accessed here[113].

[113] https://docs.google.com/spreadsheets/d/1beb8n1OrLR10cCkJl70Ytxdt6E4GaCeggAQnOYFiwQ0/edit?usp=sharing

Figure 13:

Cheniere Energy Partners Cashflow Forecast With CCS (in millions USD)

Givens				
Analyst Estimates:	*Interest expense (2028-2030 est. using 2027 figure), Net Debt, Debt Payment, Interest expense*			
Technology	*CCS*			
CCS Cost (in millions USD)	*4014*			
Inflation/Price escalation	*2.50%*			
Discount rate	*8.00%*			
Current 45Q credit rate schedule (per tonne C02 captured)	*2025: $46.96*	*2025: $50*	*2026: $50 + inflation*	
Proposed 45Q revision under Build Back Better (per tonne captured)	*$85/tonne*			
CO2 equivalent tonnes emitted (2019 basecase; thousands)	*7202.5*			
CO2 equivalent tonnes emitted (2021 estimate; thousands)	*7785.0*			
CCS capture rate	*85.00%*			
Captured CO2 eligible for 45Q credit (2019 basecase; thousands)	*6122.1*			
Captured CO2 eligible for 45Q credit (2021 estimate; thousands)	*6617.3*			
CCS fixed OPEX rate	*6.46%*			
CCS fixed OPEX year 1	*259.4*			
CCS variable OPEX inputs:				
>CCS electricity usage 2019 (MWh/tonne captured)	*0.11*	*conversion:*		*65.92*
>CCS electricity cost 2019	*$50/Mwh*	*conversion:*	*0.5*	*32.96*
>CCS electricity usage 2021 (MWh/tonne captured	*0.11*	*conversion:*		*71.25*
>CCS electricity electricty cost 2021	*$50/Mwh*	*conversion:*	*0.5*	*35.63*

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Net Debt	$ 16,370.00	$ 16,182.62	$ 15,356.15	$ 14,577.62	$ 13,836.00	$ 13,596.00	$ 13,440.00	$ 13,214.00	$ 12,988.00	$ 12,762.00	$ 12,536.00
Beginning Total Cash and Cash Equivalents (Millions $)	$1,962	$364.77	$472.19	$1,003.55	$1,792.05	$3,051.94	$4,930.04	$6,905.96	$8,873.51	$10,844.25	$12,842.64
Money In											
Net cash from operating activities	$ 1,751.00	$ 2,049.77	$ 2,527.04	$ 2,707.14	$ 2,948.01	2999.6	$ 3,018.42	$ 3,034.05	$ 3,049.74	$ 3,065.49	$ 3,081.30
Total Money In	$ 1,751.00	$ 2,049.77	$ 2,527.04	$ 2,707.14	$ 2,948.01	$ 2,999.60	$ 3,018.42	$ 3,034.05	$ 3,049.74	$ 3,065.49	$ 3,081.30
Money Out											
CAPEX	$ (972.00)	$ (747.83)	$ (148.00)	$ (135.60)	$ (103.50)	$ (101.50)	$ (101.50)	$ (101.50)	$ (135.00)	$ (135.00)	$ (135.00)
Maintenance CAPEX	$ (77.23)	$ (82.51)	$ (161.79)	$ (155.33)	$ (72.00)	$ (68.00)	$ (68.00)	$ (68.00)	$ (68.00)	$ (68.00)	$ (68.00)
Interest expense	$ (909.00)	$ (924.63)	$ (859.42)	$ (849.18)	$ (771.00)	$ (712.00)	$ (717.00)	$ (671.00)	$ (650.00)	$ (638.10)	$ (626.80)
Interest rate	5.6%	5.7%	5.6%	5.8%	5.6%	5.2%	5.3%	5.1%	5.0%	5.0%	5.0%
Net cash financing activities	$ 572.00	$ (187.38)	$ (826.47)	$ (778.53)	$ (741.62)	$ (240.00)	$ (156.00)	$ (226.00)	$ (226.00)	$ (226.00)	$ (226.00)
Total Money Out	$ (1,386.23)	$ (1,942.35)	$ (1,995.68)	$ (1,918.64)	$ (1,688.12)	$ (1,121.50)	$ (1,042.50)	$ (1,066.50)	$ (1,079.00)	$ (1,067.10)	$ (1,055.80)
Cash flow no CCS	$364.77	$107.42	$531.36	$788.50	$1,259.89	$1,878.10	$1,975.92	$1,967.55	$1,970.74	$1,998.39	$2,025.50
Distributable Cash	$ 1,644.98	$ 2,007.24	$ 2,455.47	$ 2,561.75	$ 2,196.00	$ 1,960.00	$ 1,930.00	$ 2,019.00			
With CCS Expenses and Revenues (millions)											
Interest expense with CCS	$ (909.00)	$ (924.63)	$ (904.35)	$ (1,012.86)	$ (994.68)	$ (922.21)	$ (931.14)	$ (874.83)	$ (850.89)	$ (838.80)	$ (827.50)
CCS Capex			$ (802.80)	$ (2,007.00)	$ (1,204.20)						
Net cash financing activities with CCS	$ 572.00	$ (187.38)	$ (23.67)	$ 1,228.47	$ 462.58	$ (240.00)	$ (156.00)	$ (226.00)	$ (226.00)	$ (226.00)	$ (226.00)
Net Debt with CCS	$ 16,370.00	$ 16,182.62	$ 16,158.95	$ 17,387.42	$ 17,850.00	$ 17,610.00	$ 17,454.00	$ 17,228.00	$ 17,002.00	$ 16,776.00	$ 16,550.00
CCS Total OPEX 2019 volumes						$ (292.32)	$ (299.63)	$ (307.12)	$ (314.80)	$ (322.67)	$ (330.73)
CCS Fixed OPEX						$ (259.36)	$ (265.84)	$ (272.49)	$ (279.30)	$ (286.28)	$ (293.44)
CCS Variable OPEX 2019						$ (32.96)	$ (33.78)	$ (34.63)	$ (35.49)	$ (36.38)	$ (37.29)
CCS Total OPEX 2021 volumes						$ (294.99)	$ (302.36)	$ (309.92)	$ (317.67)	$ (325.61)	$ (333.75)
CCS Fixed OPEX						$ (259.36)	$ (265.84)	$ (272.49)	$ (279.30)	$ (286.28)	$ (293.44)
CCS Variable OPEX 2021						$ (35.63)	$ (36.52)	$ (37.43)	$ (38.37)	$ (39.32)	$ (40.31)
45Q tax credit (2019 basecase)						$ 306.11	$ 313.76	$ 321.60	$ 329.64	$ 337.88	$ 346.33
45Q tax credit BBB revision (2019 basecase)						$ 520.38	$ 533.39	$ 546.72	$ 560.39	$ 574.40	$ 588.76
45Q tax credit (2021 basecase)						$ 330.86	$ 339.14	$ 347.61	$ 356.30	$ 365.21	$ 374.34
45Q tax credit BBB revision (2021 basecase)						$ 562.47	$ 576.53	$ 590.94	$ 605.72	$ 620.86	$ 636.38
Cash flow with CCS 45Q (2019 basecase)	$ 364.77	$ 107.42	$ 486.43	$ 624.82	$ 1,036.21	$ 1,681.68	$ 1,775.91	$ 1,778.21	$ 1,784.70	$ 1,812.91	$ 1,840.40
Incremental CCS value	$ -	$ 0.00	$ (44.93)	$ (163.68)	$ (223.68)	$ (196.42)	$ (200.01)	$ (189.34)	$ (186.04)	$ (185.48)	$ (185.10)
Cumulative incremental CCS value			$ (44.93)	$ (208.61)	$ (432.28)	$ (628.70)	$ (828.71)	$ (1,018.06)	$ (1,204.10)	$ (1,389.58)	$ (1,574.68)
Cash flow with CCS 45Q BBB (2019 basecase)	$ 364.77	$ 107.42	$ 486.43	$ 624.82	$ 1,036.21	$ 1,895.95	$ 1,995.54	$ 2,003.33	$ 2,015.45	$ 2,049.43	$ 2,082.83
Incremental CCS value	$ -	$ 0.00	$ (44.93)	$ (163.68)	$ (223.68)	$ 17.85	$ 19.62	$ 35.78	$ 44.71	$ 51.04	$ 57.33
Cumulative incremental CCS value			$ (44.93)	$ (208.61)	$ (432.28)	$ (414.43)	$ (394.81)	$ (359.03)	$ (314.32)	$ (263.28)	$ (205.96)
Cash flow with CCS 45Q (2021 estimate)	$ 364.77	$ 107.42	$ 486.43	$ 624.82	$ 1,036.21	$ 1,703.77	$ 1,798.56	$ 1,801.42	$ 1,808.49	$ 1,837.29	$ 1,865.39
Incremental CCS value	$ -	$ 0.00	$ (44.93)	$ (163.68)	$ (223.68)	$ (174.33)	$ (177.36)	$ (166.13)	$ (162.25)	$ (161.10)	$ (160.11)
Cumulative incremental CCS value			$ (44.93)	$ (208.61)	$ (432.28)	$ (606.61)	$ (783.98)	$ (950.11)	$ (1,112.36)	$ (1,273.46)	$ (1,433.56)
Cash flow with CCS 45Q BBB (2021 estimate)	$ 364.77	$ 107.42	$ 486.43	$ 624.82	$ 1,036.21	$ 1,935.38	$ 2,035.95	$ 2,044.75	$ 2,057.90	$ 2,092.94	$ 2,127.43
Incremental CCS value	$ -	$ 0.00	$ (44.93)	$ (163.68)	$ (223.68)	$ 57.28	$ 60.03	$ 77.20	$ 87.16	$ 94.55	$ 101.93
Cumulative incremental CCS value			$ (44.93)	$ (208.61)	$ (432.28)	$ (375.01)	$ (314.98)	$ (237.78)	$ (150.62)	$ (56.06)	$ 45.87

Remarks and Conclusions

Rising concern over supply chain emissions has prompted a greater sense of urgency among LNG exporters to address them, giving rise to the small, but growing carbon-neutral LNG market. It is increasingly clear that there will be growing competitive and regulatory pressures on LNG exporters to market supplies with a more favorable carbon footprint.

The approach that this research paper uses for estimating U.S. LNG well-to-tank emissions – utilizing the BEIS-framework used in Cheniere's first carbon-neutral trade but stripping out BEIS' estimate of shipping emissions – yields a useful reference for analyzing domestic supply chain emissions associated with U.S. LNG in the absence of more accurate emissions monitoring or the industry-wide acceptance of a standard for estimating emissions.

Facility-level emissions represent a small overall portion of total supply-chain emissions though combustion, but they are nonetheless significant. The facility-level emissions associated with the Sabine Pass LNG terminal in the case study estimate emissions at the facility level that amounts to about 41% greater emissions than what official U.S. government inventories estimate.

Before shipping, more emissions are estimated to result from the segments of the supply chain leading up to the receipt of natural gas at the liquefaction facility than from the LNG plant itself, with upstream production, processing and transportation estimated in the BEIS framework to account for about 50% of emissions. To that end, stronger U.S. government controls emissions from those operations could result in a significant decline in well-to-tank emissions associated with U.S. LNG exports and may prove critical in addressing concerns from LNG buyers about supply chain emissions, particularly methane emissions. The EPA in November 2021 proposed a regulation[114] that would require greater steps by the industry to detect and repair methane leaks and end routine flaring of natural gas from oil-focused drilling operations, with an EPA-estimated reduction of 920 million tonnes CO2e from 2023 through 2035[115]. The White House estimated that regulation could cut emissions by about 75% from covered sources, while Congress is also considering a proposed fee in the *BBB* that proponents have argued could function as an important backstop the forthcoming EPA regulations [116].

As it stands, it is not clear that investing in CCS at the Sabine Pass facility would produce positive incremental cumulative value before debt repayments by 2030 if 45Q tax incentives remain at current levels, absent new policy mechanisms that incentivize CCS or market developments that enable Cheniere to charge a sufficient premium for cleaner-LNG cargoes to cover abatement costs.

Existing publicly available cash flow projections do not span as far as 2050, which is the end year for Cheniere's existing export licenses. Having such data could make it possible to analyze the additional revenue Cheniere would need to collect to justify investing more than $4 billion on CCS, which equates to roughly $160 million on an annualized basis over 25 years. Assuming approximately 350 cargoes are exported from the Sabine Pass per year as in full-year 2019[117], and that each cargo has roughly 3.6 million MMBtu of gas, or about 3.5 Bcf, the

[114] EPA. (2021, November 15). *Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review*. Retrieved from https://www.federalregister.gov/documents/2021/11/15/2021-24202/standards-of-performance-for-new-reconstructed-and-modified-sources-and-emissions-guidelines-for.

[115] Ibid.

[116] Paul, C. (2021, December 3). *Environmental Defense Fund urges EPA to toughen oil and gas emissions rule*. S&P Global Market Intelligence. Retrieved from https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/environmental-defense-fund-urges-epa-to-toughen-oil-and-gas-emissions-rule-67928463.

[117] DOE. (2020, February). *LNG Annual Report - 2019*. U.S. Department of Energy. Retrieved from https://www.energy.gov/fecm/articles/lng-annual-report-2019

premium required to offset the CCS capital expenditure would be roughly $0.13/MMBtu. This premium is below the expected premium of about $0.15/MMBtu for "responsibly produced" gas and could be achievable as the concerns about GHG emission rise in the future. The case study assumes CCS facilities come online in 2025. Nonetheless, the ability to capture $6.6 million tonnes CO2e, based on estimated full-year 2021 volumes, emissions reported under a BEIS-well-to-tank accounting tag could be expected to fall by about 28%. The level of competitive advantage that such a reduction could provide may depend on how the trade in carbon-neutral LNG cargoes develops and whether LNG emissions accounting becomes widespread and standardized. Owners of multi-billion-dollar LNG facilities constructed on multi-decade investment horizons may find it to their benefit to foster the development of the carbon-neutral LNG market. Exporters who follow recommendations by groups such as GIIGNL to better account for absolute emissions, develop emissions-reduction plans, and report about LNG emissions with greater transparency, could prove crucial.

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