ACS Sustainable Chemistry & Engineering
pubs.acs.org/journal/ascecg
Research Article

LNG Supply Chains: A Supplier-Specific Life-Cycle Assessment for Improved Emission Accounting

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Cite This: https://doi.org/10.1021/acssuschemeng.1c03307

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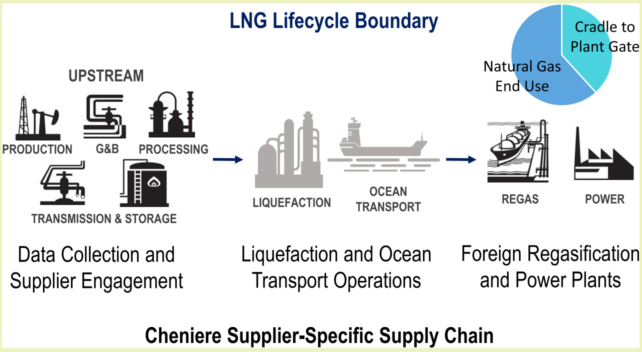
ABSTRACT: Global trade in liquefied natural gas (LNG) is growing significantly, as is interest in the life-cycle greenhouse gas (GHG) emissions associated with LNG. Most assessments of life-cycle GHG emissions from LNG have employed national or regional average emission estimates; however, there is significant variability in emissions across different suppliers and across the natural gas supply chain. This work describes a framework for compiling supplier-specific GHG emission data for LNG, from the producing well to regasification at the destination port. A case study is presented for Cheniere Energy's Sabine Pass Liquefaction (SPL) LNG supply chain from production in the United States and delivered to China. GHG emission intensities are estimated to be 30−43% lower than other analyses employing national or regional average emission profiles. The segments driving these differences are gas production and gathering, transmission, and ocean transport. Extending the boundaries of this analysis to the power plant illustrates the effect of fuel switching from coal to natural gas; the effect of fuel switching in China is a 47−57% reduction in GHG emission intensity, cradle through power generation. This work highlights the important role customized life-cycle assessments can play to improve GHG emission estimates and differentiate supply chains to inform business and policy decisions related to the transition to a low carbon future.



KEYWORDS: *liquefied natural gas, LCA, global warming, GHG, methane, supply chain, carbon, carbon neutral*

INTRODUCTION

The global LNG industry has experienced a period of rapid growth, reaching a record ~355 million tonnes (MT) traded in 2019 (~13% increase from 2018).[1] In the United States (U.S.), large-scale LNG exports from the lower 48 states are a recent phenomenon with the start of operations at Cheniere's Sabine Pass Liquefaction (SPL) facility in 2016. U.S. LNG exports grew almost 13-fold from 2016 to 2020, from ~3.7 to ~46.8 MT, and have been delivered to 36 countries and regions.[2] Continued growth for LNG exports is forecast, with expectations for future global demand ranging from ~450[3] to ~700 MTPA by 2040.[4]

Concurrently, significant reductions in greenhouse gas (GHG) emissions are needed to align with the Paris Agreement goals to limit global warming to well below 2 °C.[5] Methane (CH_4) and carbon dioxide (CO_2) emissions from the LNG life cycle and natural gas end uses vary widely across different regions and supply chains, even as measurement data are still missing across many regions and industry segments.[6−9] Relative to traditional piped gas supply chains, LNG supply chains include liquefaction, shipping, and regasification stages which drive even greater variability in emissions profiles. For example, Gan et al.'s review of 37 global LNG supply scenarios to China concludes that GHG intensities varied by about 150%.[10]

Reducing GHG emissions across natural gas supply chains has become a key policy focus for many countries.[11−16] The European Union, whose gas imports account for about 36% of the total international natural gas trade,[17] is considering climate policy that includes embodied emissions associated with imported natural gas.[18] Accounting for such upstream emissions across national boundaries marks a departure from the standard production-based emission inventories.[19] However, a lack of standardized quantification, monitoring, reporting, and verification (QMRV) measures hampers the differentiation of emissions between different import routes and supply chains. This may result in the use of "default" emission factors[20] within corporate and government policies, which do not accurately reflect the variation in GHG emissions. Certain firms have responded to anticipated policy changes and buyer interest by

Received: May 17, 2021
Revised: July 16, 2021

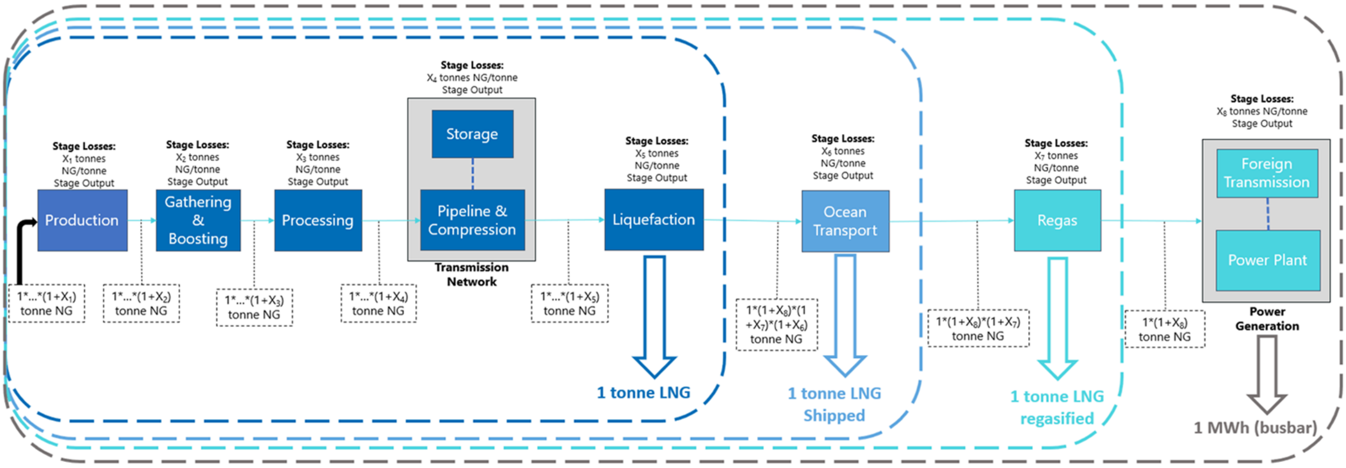


Figure 1. Life-cycle scaling and system boundaries used in this work. For each boundary, the supply chain losses (fugitives, venting, fuel consumption, etc.) are tracked and used to scale the process upstream of the functional unit (end point of the supply chain).

committing to provide life-cycle emission information, raising the possibility of more granular and reliable accounting.[21,22]

Reliable tools and data for estimating GHG emissions for supplier-specific LNG supply chains are needed to boost confidence in climate-driven policy decisions. To date, estimates of LNG supply chain emissions have not been supplier specific but national or regional in scope, often relying on generic emission factors and activity data to fill extensive data gaps.[23−25] We are unaware of any public study that incorporates detailed supplier-specific activity data to estimate bottom-up facility-level emissions across the LNG supply chain, including for natural gas liquefaction and ocean transport (see Supporting Information (SI) 15).[10,24,26−30] Current studies rely on national or regional emission data, but even at this level of aggregation highlight the importance of emission upstream of end use (power plant). The studies estimate that upstream GHG emissions account for 20−45% of wellhead through power plant CO_2e emissions on a 100 year basis, depending on exact scenario.[24,26,30,31]

Cheniere is the largest LNG exporter from the U.S. in terms of volumes exported as of the end of 2020.[2] This study develops an LCA framework to estimate GHG emissions representative of Cheniere's SPL LNG supply chain. This study conducts a uniquely detailed analysis mapping the LNG supply chain both upstream and downstream from Cheniere's SPL facility for 2018 using supplier-specific data collected from wellhead through ocean transport. This analysis is the first of its kind in customizing emissions data sources across the supply chain to derive a representative profile of an LNG firm's life-cycle GHG emissions. The improvements to life-cycle GHG emission methodologies made in this work are:

1. Data from specific producers and transporters of natural gas from wellhead to liquefaction: Emissions are reported for the specific supply chain used by Cheniere and include operational data that enable a more accurate estimation of emission intensities.
2. Supplier-specific liquefaction data: Most previous assessments have used generic engineering analyses of liquefaction; this work uses supplier-specific liquefaction emission intensity data.
3. LNG ocean transport: generic operating assumptions (e.g., the type, propulsion system, and size of ships used to transport LNG) are replaced with actual fleet data collected from operations.

This supplier-specific approach to assessing life-cycle GHG emissions moves away from generic default data inputs to reduce uncertainties around emission intensity estimates. By working with their supply chains to gather data, LNG suppliers can better characterize the full scope of their GHG emission intensities and identify opportunities for emission abatement. By demonstrating how to develop a supplier-specific LCA for LNG, this work suggests LNG LCA accounting methods that can be relied on for future policy initiatives.

■ METHODS

GHG emissions are estimated for the LNG supply chain for the SPL facility. The primary functional unit is 1 tonne LNG shipped to a destination port; however results are also reported for functional units of 1 tonne LNG liquefied, 1 tonne LNG regasified at a delivery port, and a mega-watt hour (MWh) of electricity generated in a destination market. We present a case study of LNG delivery to China for use in electricity generation, comparing LNG used for natural gas power generation with coal power generation on an equivalent MWh basis to highlight the importance of upstream (wellhead to regasification) emissions. The analysis accounts for emissions from the following natural gas industry segments: production, gathering and boosting (G&B), processing, transmission compression, transmission storage, transmission pipeline, liquefaction, ocean transport, regasification, foreign pipeline transmission, and power generation (SI 1−5). Figure 1 illustrates the study boundaries considered in this paper, alongside the life-cycle scaling approach.

The LCA is conducted in accordance with the International Organization for Standardizations (ISO) 14040, 14044, and 14067 standards (SI 16).[32−34] The model is structured using a unit process approach and accounts for over 125 unique sources of greenhouse gas emissions and over 50 unique unit processes (SI 2−5). Using a unit process structure for each emission source, the energy and material flows are accounted from a bottom-up emission source basis to a facility and segment within the supply chain. The LCA model constructed in this study is based on the publicly available National Energy Technology Laboratory (NETL) upstream supply chain model for the production, G&B, processing, transmission and storage (here referred to as upstream) operations.[35] The upstream model was populated with parameters representing Cheniere's SPL supply chain, using Subpart W of the Environmental Protection Agency (EPA) Greenhouse Gas Reporting Program (GHGRP) as the key activity and emissions data source.[36] Several improvements were made to the underlying NETL model to better represent Cheniere's SPL supply chain, reflect the current state of the science, and incorporate additional GHGRP emission data (vintage 2018, detailed in SI 2.9). These improvements were complemented with the inclusion of additional data from suppliers on key emission sources at facilities not required to report to the GHGRP, ensuring representativeness of operations and complete accounting of sources (SI 1 and 2). Statistical bootstrapping was used to create parameter distributions of the average value for each supplier-informed parameter. These parameters include total emissions, activity data (e.g., counts of equipment, volumes of fuel used), and throughput data. Statistical methods are further explained in SI 2.1 and parameters are documented in SI 2.10.

Our study employs a combination of the ONE Future Methane Emission Estimation protocol and the Natural Gas Sustainability Initiative (NGSI) Methane Emission Intensity protocol to handle the co-production of condensate and gas in upstream operations.[16,37] We use a combination of partitioning (assigning an emission source wholly to a specific product—gas or liquids) and energy-based allocation (apportioning an emission source to co-products based on their energy content). We more closely align with the ONE Future partitioning and allocation method, with four deviations: associated gas venting and flaring, completion and workover venting, and liquids unloading venting emissions are energy allocated in our work between the produced gas and lease condensate streams. Further, we use partitioning to account for fugitives at production and G&B, detailed in SI 2. As outlined in the NGSI protocol, for production and G&B energy allocation, this study assumes 1.235 million British thermal units (MMBtu)/thousand cubic feet (Mcf) of produced gas (before removal of natural gas liquids) and 5.8 MMBtu/barrel (bbl) for lease condensate.[37] For processing facility emission energy allocated between pipeline quality gas and natural gas liquids (NGLs) exiting the facility, we assume 1.031 MMBtu/Mcf for pipeline gas and 3.82 MMBtu/bbl for NGLs (as outlined by NGSI).[37] To further align with these protocols, the NETL model was modified to include emission modeling for associated gas venting, associated gas flaring, and atmospheric storage tanks. These and other updates are documented in SI 2.

A new liquefaction unit process was created using facility-specific emissions and energy consumption data for SPL using the GHGRP Subpart W and Subpart C (see SI 3 for details). A new model of ocean transport was developed using 2018 voyage log and proprietary vessel data for cargos loaded with Cheniere SPL LNG in 2018. The voyage log data were used to estimate the market-level weighted average ocean transport intensity of all cargoes loaded at SPL in 2018 and delivered to a foreign port. All data sources and calculations are documented in SI 4. Regasification, foreign transmission, and power generation unit processes were built from published literature, third-party data sets, and engineering estimates, which are further detailed in SI 5.

The results are compared to an LCA of Chinese coal power generation, using recently published data on Chinese coal mine methane (CMM) and coal power plant fleet average efficiencies, with both parameters highly regionalized.[38−41] This modeling work is further documented in SI 8.

Total GHG emissions are estimated using the IPCC Fifth Assessment Report (AR5) global warming potentials (GWP) for methane and nitrous oxide (N_2O). To reflect the different climate impacts of these GHGs across timescales, we present results across the two typically used timescales, 100 year ($CH_4 = 36\ gCO_2e/gCH_4$, $N_2O = 298$, $CO_2 = 1$) and 20 year ($CH_4 = 87$, $N_2O = 268$, $CO_2 = 1$). These factors account for both the climate-carbon feedback effects as well as CO_2 produced from atmospheric methane oxidation.[42]

The framework presented in this study improves previously published LNG studies by customizing supply chain operations from production to the regasification plant. Past studies have employed regional (e.g., oil and gas basin) or national level for upstream (production through transmission) emission factors or activity data and use generic, engineering-based estimates of liquefaction and ocean transport for the LNG supply chain. Our supplier-specific LCA employs facility-level emissions and operations data for the known gas suppliers upstream of SPL liquefaction and models actual operations for the SPL facility and each unique LNG cargo loaded and shipped at SPL in 2018 using cargo-specific data. No previous LCA of LNG has customized the supply chain to this level.

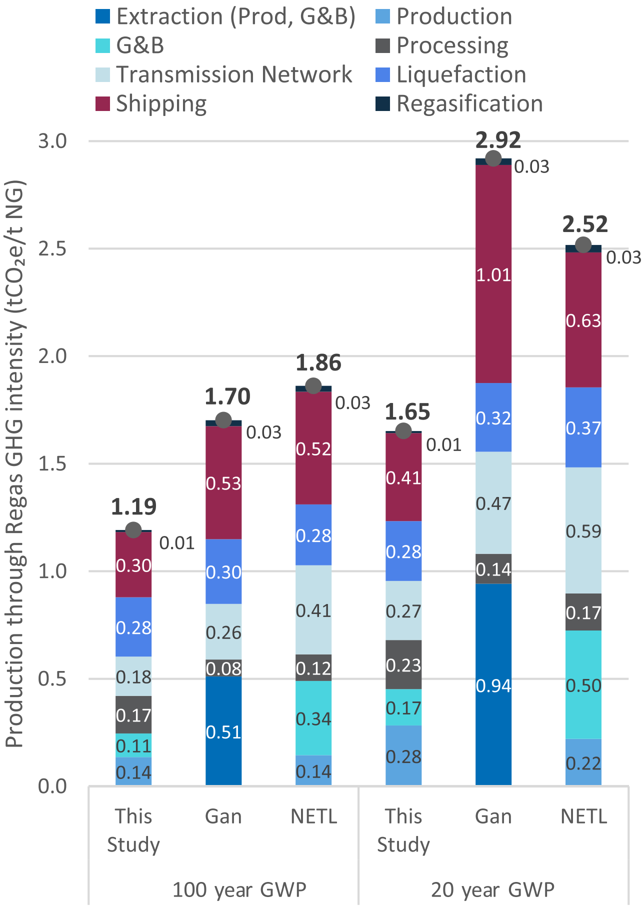


Figure 2. Greenhouse gas emission intensity, attributed to individual life-cycle stages for this work, compared to two similar assessments of emission intensity from U.S. LNG transported to China (Gan et al.; NETL).[10,26] While each of the studies estimated an uncertainty range around the expected result in the original published work, the data for Gan et al. and NETL were not published with sufficient granularity to allow error bars to be reconciled and shown in this work on a comparable basis.

RESULTS AND DISCUSSION

Figure 2 displays GHG emission intensity results for the Cheniere SPL supply chain up to regasification in China and compares to two similar assessments of emissions intensity from the U.S. LNG transported to China (Gan et al.; NETL).[10,26] This study estimates a GHG intensity 30−43% lower than the Gan et al. study, and 34−36% lower than the NETL study considering the 100 and 20 year GWP time horizons. The Gan et al. result is the average of 21 scenarios for U.S. LNG exported from the Gulf Coast to China, with each scenario representing a different U.S. production techno-basin (combination of natural gas basin and extraction technology). The NETL scenario models Appalachian Shale gas as the gas source, and LNG exported from the Gulf Coast region. The reconciliation performed to allow equivalent comparison of the NETL and Gan et al. studies with this study is documented in SI 9.

Emissions from the production and gathering and boosting stages for this study are approximately 52% lower than the estimates by Gan et al. on both the 100 and 20 year basis, and 38−50% lower than the estimates by NETL on the 20 and 100 year time horizons, respectively. There are two key reasons for these differences. First, there are differences in data vintage included in each assessment. Gan et al. rely on upstream data

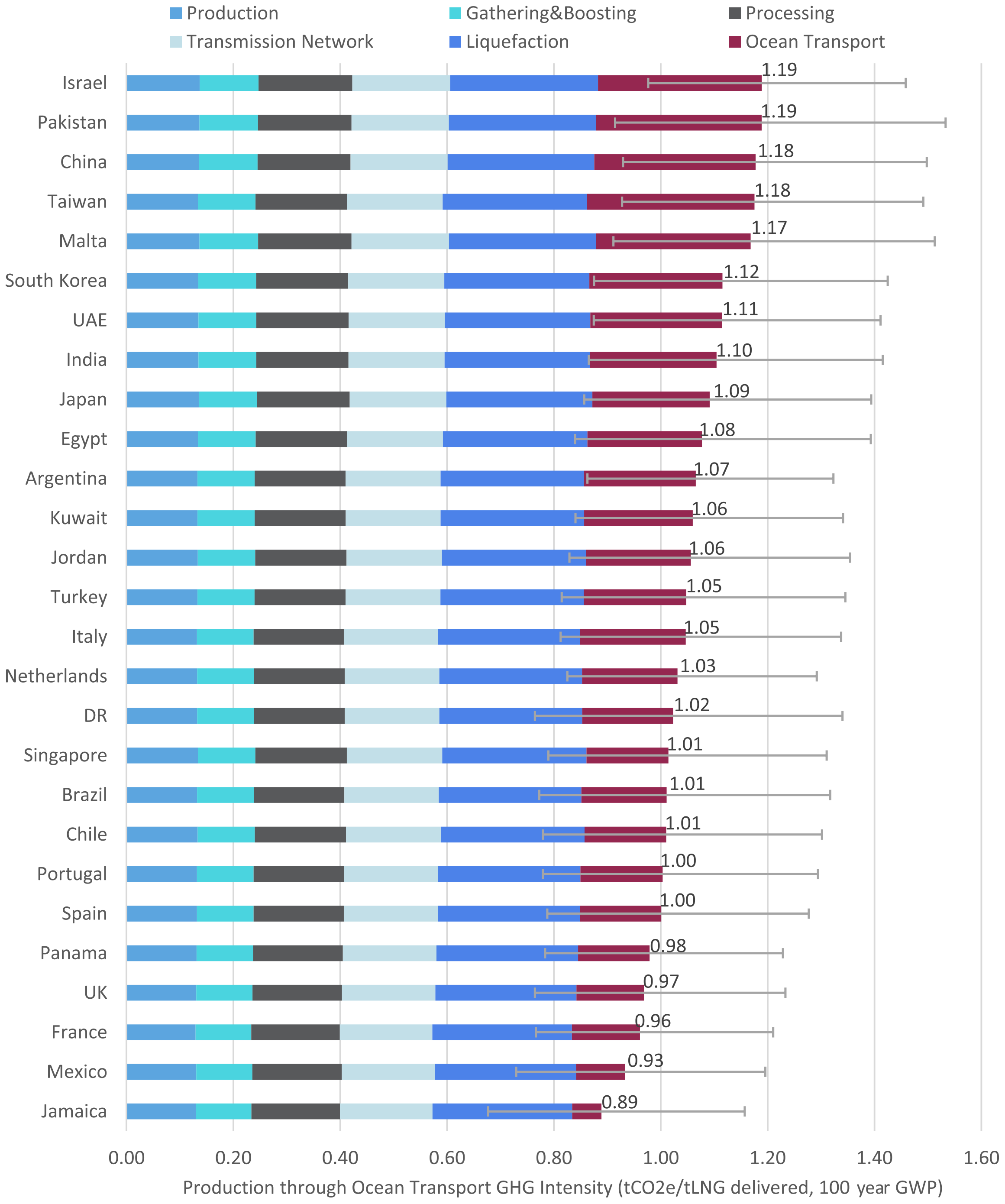


Figure 3. GHG emission intensity from production through ocean transport by market; ocean transport emission intensities range from 0.05 tCO_2e/t delivered and a 6% contribution to the life cycle total (Jamaica) to 0.31 tCO_2e/t delivered and a 27% contribution (Taiwan). Since emissions are normalized to per tonne of LNG delivered, we observe differences in the upstream GHG intensity. Though the upstream supply chain modeled is the same for each scenario above, the losses (consumption of natural gas) during ocean transport vary among the scenarios, leading to differences in the calculated GHG intensity of production through liquefaction when the supply chain is normalized to LNG delivered.

collected in 2012 (published in the 2016 NETL upstream report[43]), while the supplier-specific data reported in this work are from 2018. In 2018, additional regulations have required the use of reduced emission completions and other emission reductions compared to 2012,[44,45] and production-stage GHG emissions have been reported to be reduced by 50%.[46,47] Second, emission intensities among the producers in Cheniere's supply chain are lower than the basin-level average characterization in Gan et al. Figure 2 shows the average of the 21 U.S. LNG scenarios modeled in Gan et al. (extraction intensity 0.51 tCO_2e/t regasified on a 100 year basis), but the scenarios span a wide range of extraction intensities from 0.22 (Gulf of Mexico Offshore gas) to 1.06 (North Central shale gas source) tCO_2e/t regasified. The Cheniere supply chain average extraction emission intensity, for reference, is 0.25 tCO_2e/t regasified.

The NETL 2019 study uses more recent production emission data (2016 data) than Gan et al. and is based on natural gas production in Appalachia with relatively low emission intensity.

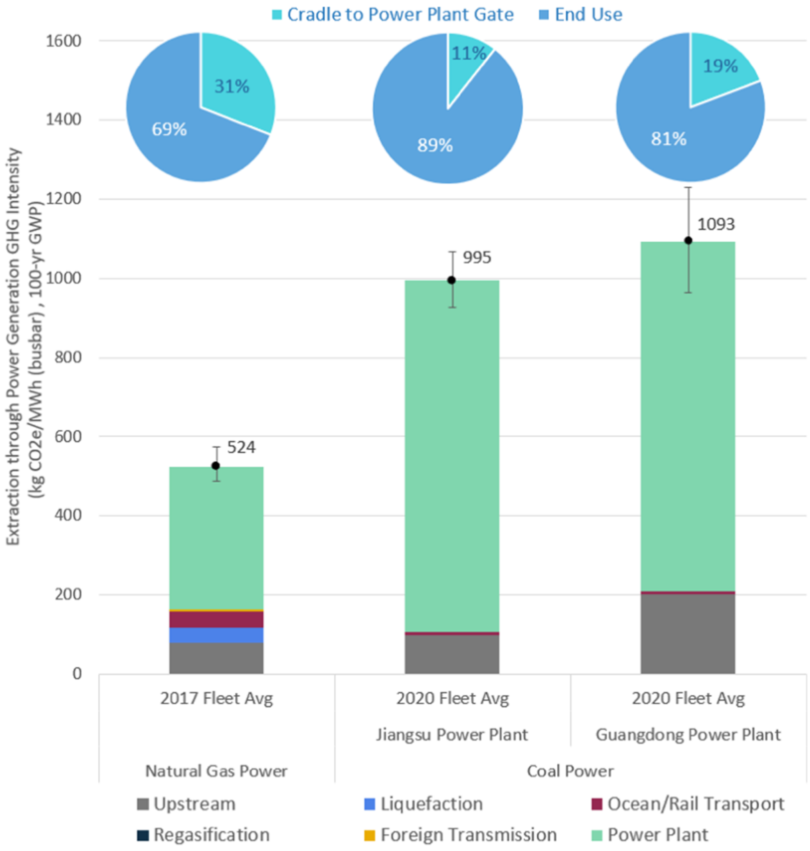


Figure 4. Comparison of the supplier-specific natural gas power generation scenario to coal-fired power generation at two locations in China. The stacked-bar portion of the figure shows the stage-level contribution to the cradle through power generation (busbar) GHG intensity. Above each bar is a pie chart that shows the percent contribution of end use (power plant) vs cradle to power plant gate supply chain emissions.

The NETL analysis differs from this study primarily in the G&B and transmission stages. The differences in G&B intensity appear to be driven by differences in individual facility performance. To model transmission compression, the NETL model uses a factor of 0.97 horsepower-hour (HPh)/Mcf to estimate the transmission station throughput (derived from NETL published parameters). The average ratio of HPh to Mcf of throughput, from Cheniere's known suppliers, is 0.27 HPh/Mcf, based on supplier data collection done in this work. For modeling gas from other transmission operators, the GHGRP does not publicly provide the throughput of compressor stations so this study assumes 0.29 HPh/Mcf based on data from the Energy Information Administration (EIA) and Inventory of U.S. Greenhouse Gas Emissions and Sinks (GHGI). The higher factor used in the NETL work results in increased fuel consumption across the transmission network. The updates to transmission compression are further discussed in SI 2.

Cheniere's liquefaction GHG intensity is 8−13% less than that estimated by Gan et al. and is comparable to the NETL study estimate on a 100 year basis. This study models liquefaction directly using SPL emission reporting and operational data from 2018. Details are provided in SI 3. Gan et al. also based their figures on SPL but used prospective estimates from the 2011 Environmental Assessment report when SPL was not yet operational.

The Cheniere ocean transport stage emission intensity is 42−60% less than Gan et al., 100 and 20 year GWP, respectively. Compared to NETL, ocean transport emission intensity is 42−35% less, based on 100 and 20 year GWP, respectively. Our study utilizes recorded fuel consumption and proprietary vessel and third-party data collected from LNG carrier voyages in 2018, whereas NETL and Gan et al. base their emission calculation on a theoretical ship of a specific size and propulsion system, estimating the voyage duration based on distance and speed assumptions. Further, Gan et al. assume that 20% of all generated boil-off gas (BOG) is emitted to the atmosphere (it is unclear whether this is fugitive, slip, or venting emissions). Based on guidance from industry experts, our model assumes all BOG is used for propulsion and to meet vessel's electric load demand ("hotel load"), where engine slip is 0.10−3.13% of engine throughput, depending on the propulsion system.[48] Detailed voyage-specific operational data enables accurate accounting of key parameters, including BOG management rates and propulsions systems, resulting in much-improved assessment of the ocean transport segment. Fugitive emissions from LNG carrier operations are assumed negligible based on an understanding of operational practices, but no data is yet available for corroboration. Further, while this study accounts for variability in efficiency and methane slip across propulsion types, the impact of methane slip from the smaller auxiliary engines is unknown. This study accounts for total fuel demand for both the laden and ballast voyages (used for propulsion and hotel load) but assumes that all fuel is combusted in the main engine propulsion system. The difference in emission performance between the larger, continuous propulsion engines and the smaller generator engines is understudied and an opportunity for improvement in the modeling of LNG ocean transport.

The results in Figure 2 demonstrate the importance and value of supplier-specific LCA. Modeling a national- or regional-level average of the natural gas production through the transmission

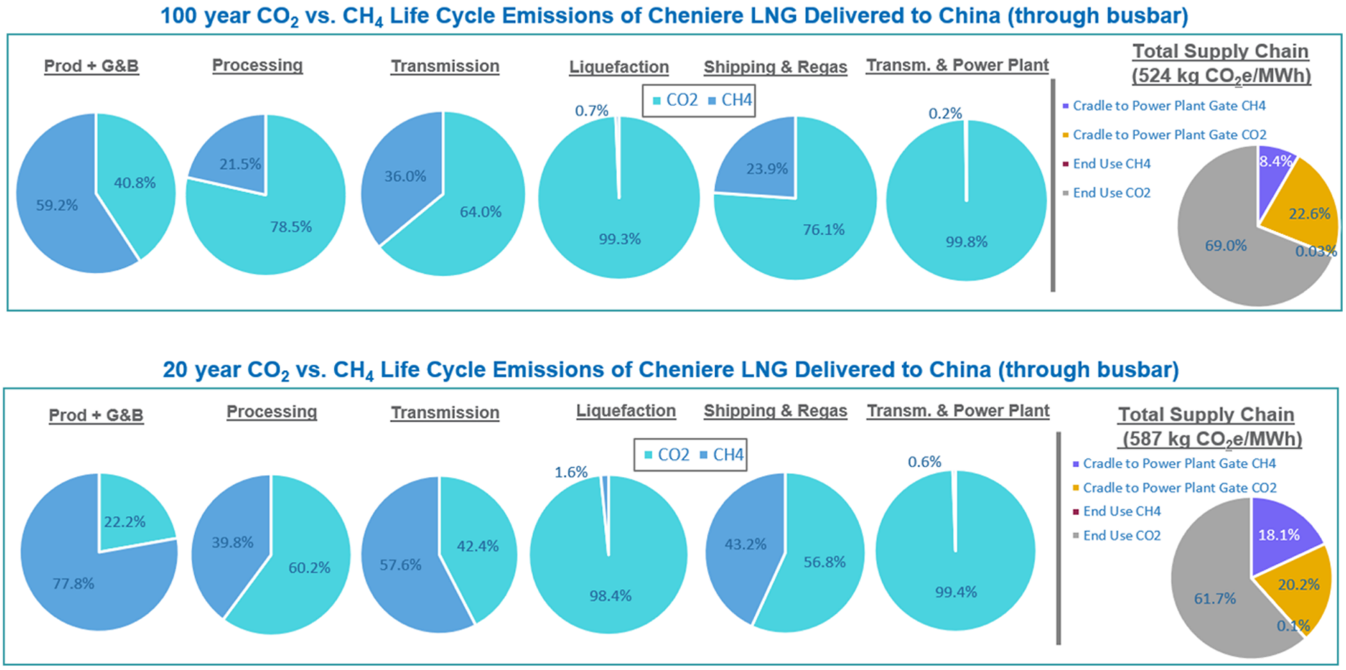


Figure 5. Contributions of CO_2 and CH_4 on a CO_2e basis across the supply chain stages for natural gas.

supply chain is not representative of each unique supply chain due to the significant variability in individual operator performance primarily driven by the source and transport of the natural gas and LNG. While for this specific year and supply chain, the customized LCA resulted in a lower GHG intensity than other study estimates, there will also be supply chains with greater GHG intensity than the average, depending on the sourcing and transportation of gas and LNG. Understanding this variability will be critical for characterizing the true emission intensity of different LNG supply chains and enables differentiated LNG supply for natural gas consumers with climate goals.

LNG Market Customization. Figure 3 shows the market-level weighted average GHG intensity from wellhead production through ocean transport for the 27 markets which received LNG from SPL in 2018. The error bars represent the 95% confidence interval in the average result, capturing uncertainty and variability across the supply chain. The ocean transport model created for this study models at the individual round trip voyage level, allowing for a unique emissions profile for any cargo. Individual cargos were weighted by the volume of LNG delivered to the regasification terminal to obtain a market average. These market-level averages demonstrate the varying contribution of ocean transport to the production through ocean transport life-cycle intensity. This difference is driven by a combination of voyage distance and the propulsion system of the LNG carrier. Within a given market, there is often variability between the GHG intensity of individual voyages due to voyage duration, as well as differences between vessel performance. Further, we see how influential the individual cargo performance can be on the GHG intensity. Pakistan and India share similar voyage lengths, but Pakistan's GHG intensity is 8% higher on a production through ocean transport basis. The effect of a ship's propulsion system is explored further in SI 4, using the United Kingdom (U.K.) and China as case studies.

Natural Gas End Use. Figure 4 exhibits the GHG emission intensity from the Cheniere SPL LNG supply chain through power generation in China, compared to coal power generation as a case study. Two coal scenarios are modeled since coal mine methane (CMM) emissions differ significantly between northern and southern China: the Jiangsu scenario represents coal mining and power generation in a northern province; Guangdong represents a southern province.[38] The LNG scenario represents Cheniere's weighted average supply chain of SPL export to China in 2018, weighting individual cargoes based on LNG volume delivered, modeled with a fleet average power plant efficiency of 2017 vintage due to data limitations (see SI 5 for details).[49] The error bars represent the 95% confidence interval in the average result, capturing uncertainty and variability across the supply chain.

Similar to the variation in methane emissions from natural gas, CMM emissions in China can vary by more than an order of magnitude across source regions and whether a mine is subject to methane outbursts. The GHG intensity of the upstream coal supply chain ranges from comparable to more than double the Cheniere upstream LNG supply chain. While out of the scope of this study, it will be important to characterize supplier-specific emissions for coal in future research, similar to what is done for natural gas in this study. The provincial average extraction data for northern coal-producing provinces near Jiangsu and Southern coal-producing provinces near Guangdong is combined with provincial average data on power plant performance for Jiangsu and Guangdong to generate the levelized GHG intensity.[40] The GHG intensity of the supplier-specific natural gas power scenario is estimated to be 47−52% less intense than the regional coal power generation scenarios on an equivalent MWh basis, 100 year GWP basis.

For the LNG supply chain, the majority of the GHG emissions occur at the power plant during combustion for power generation and are a function of the power plant efficiency and fuel composition. However, the production to power plant gate emissions are significant, ∼31% of CO_2e on a 100 year basis and ∼38% on a 20 year basis for LNG exported to China for power (20 year GWP results shown in Figure 5 below). Given the

Table 1. Supply Chain GHG Intensity Results for the Four Boundaries Examined in This Study, Cradle through Liquefaction, Ocean Transport, Regasification, and Power Generation[a]

	100 year			20 year			
boundary	P97.5	exp	P2.5	P97.5	exp	P2.5	units
cradle through liquefaction	1.05	0.82	0.63	1.51	1.15	0.86	t/t liquefied
cradle through shipping (China)	1.5	1.18	0.93	2.12	1.64	1.26	t/t shipped
cradle through regasification (China)	1.51	1.19	0.94	2.13	1.65	1.28	t/t regasified
cradle through power generation (China)	573.2	524.4	485.9	657.9	586.8	531.2	kg/MWh (busbar)

[a] Results are shown on a CO_2e basis for the China supply chain.

significance of emission upstream of the power plant for the natural gas supply chain, supplier-specific estimates of GHG intensity will be critical for analyzing differentiated gas supplies.

Figure 5 breaks down the relative contributions of CO_2 and CH_4 on a CO_2e basis across the supply chain stages for natural gas. The majority of CH_4 emissions occur in the production, processing, transmission, and shipping segments of the supply chain, with methane emissions accounting for about 60% of the production profile. Impacts of methane emissions are amplified under the 20 year basis. The majority of the emissions occur at the power plant during combustion for power generation and are a function of the power plant efficiency and fuel composition. A similar breakdown of CO_2 vs CH_4 is provided for coal supply chains in SI 12.

To summarize the baseline results of this study, Table 1 shows the 100 and 20 year GWP GHG intensities of the four boundaries examined in this study, using electricity generation in China as an end-use example. A detailed breakdown of results by the supply chain stage can be found in SI 13.

Sensitivity Analysis. This work demonstrates that the use of current supplier-specific data is vital for accurately accounting for the variability of GHG emissions from natural gas. As methane emissions are reduced further in response to regulations (e.g., from the US,[44,45] EU,[18] Mexico,[50] and Canada[13]), voluntary initiatives (e.g., EPA Methane Challenge ONE Future and BMP,[51] OGMP 2.0[14]), and through corporate GHG commitments, these estimates should evolve. The baseline methane emission intensity expressed as mass of methane emissions per mass of LNG exiting liquefaction from this work is estimated to be 0.65% (SI 11). To investigate the impact of methane emission reductions on GHG emission intensity (CO_2e), a sensitivity analysis was performed on methane emission sources in production, G&B, processing, and transmission operations. The modeled baseline represents the 2018 average of Cheniere SPL's production through liquefaction supply chain. Methane emissions were reduced by fixed percentages to be technology-agnostic. Figure 6 shows the production through liquefaction life-cycle GHG emissions intensity (for 100 and 20 year GWP) as upstream methane emissions are reduced by up to 50% relative to the baseline of this study (wellhead through liquefaction boundary). A 50% reduction in methane emissions translates to a 14% decrease in 100 year CO_2e emissions (wellhead through liquefaction) and 24% decrease in 20 year CO_2e. The ideal emission mitigation approach will be supplier-specific, targeting the unique characteristics of each facility. This points to the importance of supplier-specific LCA as a decision-making tool for emission mitigation.

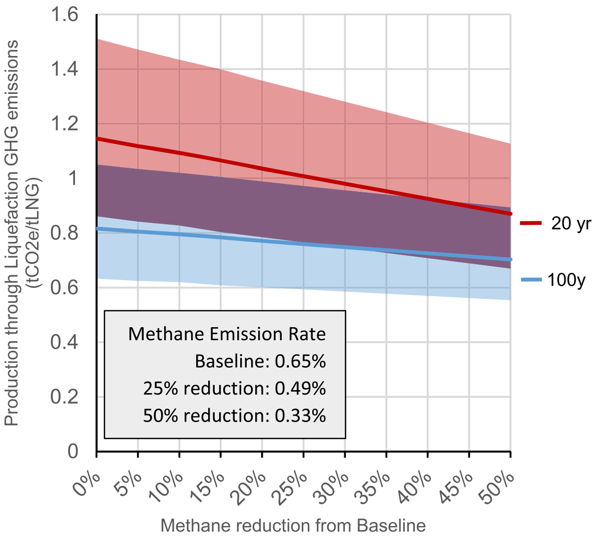


Figure 6. Impact of decreases in methane emissions on production through liquefaction life-cycle greenhouse gas emission intensity; a 50% decrease in wellhead through transmission methane emissions translates to an estimated methane emission rate of 0.33% (wellhead through liquefaction basis). The shaded blue region represents the 95% confidence interval in the average value for the 100 year GWP. The shaded red region represents the 95% confidence interval in the average value for the 20 year GWP. Where the 100 and 20 year confidence intervals overlap, the area is shaded purple.

Another sensitivity analysis is conducted to assess potential sources of under-reported emissions within the GHGRP, as identified in recent studies by Lyon et al. and Rutherford et al.[52,53] These analyses demonstrate how discrepancies in emission inventories and top-down studies can be reconciled in part with improved emission factors and assumptions on operations. Here, we investigate the sensitivity of the supply chain to production and G&B fugitive emission factors, emissions from tank thief hatches and other gas release points from tanks, and flaring efficiency in the Permian oil and gas production region in the U.S. The GHGRP assumes flaring emissions from a destruction efficiency of 98% and relies on national average values per source for fugitive emission factors, both of which have been shown to vary widely by Lyon et al. and Rutherford et al. When the Permian flare efficiency is modeled as 93% for known suppliers, the net effect on the GHG intensity in this study is less than a 1% increase on a 100 year GWP basis (wellhead through regasification basis) since the SPL supply chain had relatively few Permian basin suppliers in 2018. Modeling deterministically the average fugitive emission factors proposed by Rutherford et al. results in a less than 1% increase in the GHG intensity on a 100 year GWP basis (wellhead through regasification basis). However, as described in SI 7, uncertainty surrounding emission factors used for production and G&B fugitives may lead to larger impacts. Finally, the sensitivity on atmospheric storage tank thief hatches and other gas release points on tanks resulted in a 5−6% increase in production through regasification GHG intensity on a 100 year GWP basis. Sensitivity analyses and results are further documented in SI 7.

This work utilizes the most granular level of supplier activity data available and employs the latest state of the science on GHG emissions. However, we recognize that there are limitations to the data and opportunities for future improvement. We address the known limitations of the GHGRP emission factors through a sensitivity analysis on modeled parameters.[52−54] The supplier-specific supply chain model is limited by the lag in data reporting from the GHGRP (data is generally published in the third or fourth quarter of the following year, i.e., 2018 data becomes available toward the end of 2019) as well as the unknown surrounding gas purchased from nonoperators (e.g., marketers). These volumes purchased from nonoperators are currently modeled using a US average intensity, but future efforts will focus on improving this understanding.

Policy Implications. This study highlights the wide differences in emissions intensities across different supplier routes at a time where interest in accounting for embedded emissions is growing among companies, policymakers, and investors.[55] In the European Union, policymakers are contemplating the development of a Carbon Border Adjustment Mechanism and a Methane Supply Index (MSI) to compare the GHG and methane footprint of different gas supplies for future policy considerations and "empower buyers to make informed choices."[56] The Japanese government has launched a review of its policies related to meeting its 2050 carbon-neutral target, including potentially embarking a carbon-neutral roadmap for its LNG supply chain.[57] Meanwhile, investors have become more focused on climate-related disclosures, including GHG emissions, as evidenced through broader adoption of frameworks such as the Taskforce for Climate-Related Disclosures (TCFD) and alignment of investment portfolios with Paris Agreement goals.[58]

Such market and policy trends are nascent but not hypothetical. At least two long-term LNG supply and purchase agreements that include statements of GHG emissions have been signed, and over a dozen carbon-neutral LNG (CNL) commercial transactions have been undertaken recently (see SI 14).[59,60] A group of major Japanese LNG buyers have formed a Carbon-Neutral LNG Buyers Alliance to support the greater use of CNL.[61] CNL combines the delivery of LNG with offset credits commensurate with its estimated life-cycle emissions footprint. Kasumu et al. observe that trade agreements could do a better job accounting for embedded emissions and using an LCA for LNG emission accounting.[62]

Quantified GHG emissions, CNL, and future market transactions first require improving buyer confidence in the comprehensiveness and accuracy of emission assessment and reporting, and such assessments are only as effective as their ability to account for all relevant GHG emissions from each segment across the natural gas supply chain. More discerning consumer demand may therefore stimulate the private sector to improve emission estimates.

As such, public[35] and private GHG accounting for the LNG supply chain would benefit from a level playing field with a common set of transparent supplier-specific standards for LNG emission accounting. For instance, minimum requirements in accounting for emission sources within each supply chain and transparent data sources and modeling assumptions would strengthen accounting foundations. The U.S. benefits from robust and transparent regulatory reporting of GHG emissions data via GHGRP, which can be further improved by additional QMRV measures.

Harmonized data collection and reporting would build confidence in supplier claims about LCA emissions, enabling comparisons between natural gas supply chains and supporting climate goals for all participants in the supply chain. This could stimulate a virtuous cycle of demand for GHG accounting and reduction and provision of more granular, company-specific emissions estimates.

CONCLUSIONS

As countries and companies develop climate goals, it is vital to have consistent and transparent analytical frameworks to account for emissions across the life cycle of the product. Natural gas and LNG supply chains are highly variable; as such, this work demonstrates the benefits of a customized LCA rather than relying on generic national or regional data. This study conducts a supplier-specific LCA of Cheniere's SPL LNG supply chain that advances the understanding of life-cycle LNG GHG emissions, demonstrates the improved accuracy of actual data vs modeled assumptions, informs areas for mitigation of GHG emissions, and presents an LCA framework that can be adopted by other stakeholders.

The results demonstrate improved emission intensity estimates between this specific supply chain and ones modeled using national averages and generic assumptions. This study finds a 30−43% decrease in GHG intensity relative to other studies employing generic national or regional data (wellhead to regasification). This is significant, as our study demonstrates that emissions upstream of end use (production to power plant gate) account for ∼31−38% of GHG emissions from cradle through power generation (100 and 20 year GWP, respectively, LNG export to China supply chain).

The study also produces a unique ocean transport model using representative fuel and emission data from LNG transport routes out of SPL in 2018. Results show that ocean transport emission intensities are ∼35−60% lower than other studies, and there exists high variation across transport routes and ship propulsion technologies.

Further, this study finds a methane emission rate, wellhead to liquefaction, of 0.65%. A sensitivity analysis on methane emission reductions estimates that a 50% reduction in upstream methane would result in a 14−24% reduction of supply chain emissions (wellhead to liquefaction, CO_2e 100 and 20 year GWP basis, respectively).

In addition to demonstrating the value of a customized supply chain LCA, this work has important implications for methane's role in the LCA of LNG. While CO_2 is a significant portion of total GHG emissions on a CO_2e basis, these emissions are well understood and occur primarily at the power plant or during other (easily estimated) end-use combustion activities. Conversely, CH_4 emissions are more variable and less understood. Also yet, there is a growing recognition that methane emissions—which occur largely upstream of the power plant—also constitute a significant portion of CO_2e life-cycle emissions for the LNG supply chain, 8.4% of cradle to power generation emissions on a 100 year GWP basis and 18.1% on a 20 year GWP basis for China. Similarly, we observed the upstream of end use methane impact in coal supply chains (primarily from CMM), which constitutes ∼10−35% of total CO_2e on a cradle to power generation basis for the two Chinese coal provinces investigated (100−20 year GWP, as shown in SI 12). Improving our understanding of methane emissions will be critical for modeling differentiated LNG and natural gas supply chains and therefore gaining a more accurate accounting of emissions from LNG.

As policymakers and companies develop their climate strategies, it is imperative to accurately account for supplier-specific emissions, include all relevant emission sources, and employ appropriate practices for allocating between liquid and gas supply chains. Enhanced QMRV measures across the gas and LNG supply chain will improve GHG estimates employed as part of a customized LCA model. A customized LCA allows for more accurate understanding of GHG emissions if the underlying data is robust and the methodology consistent, and serves as the baseline for the next step toward designing appropriate policies and corporate strategies to transition to a lower carbon future.

Commercial preferences may also inform public policy at domestic and international levels, leading for instance to integration of climate and trade policy. GHG emission accounting frameworks will be increasingly important as the industry navigates competitive landscapes between those jurisdictions that do and those that do not account for emissions.[63] Taken together, these evolving commercial and public policy trends are moving in the same direction—greater incentives for robust, transparent, bespoke, and verifiable LCAs.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.1c03307.

Details of emission estimation methods, sources of activity data and emission factors, and sensitivity analyses (PDF)

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Funding

This work was funded by Cheniere Energy Inc.

Notes

The authors declare the following competing financial interest(s): F.C.G. and G.R. are employees of Cheniere. One of the authors (D.T.A.) has current research support from multiple natural gas producers, the Collaboratory to Advance Methane Science, and Environmental Defense Fund. D.T.A. has done work as a consultant for multiple companies in recent years, including British Petroleum, Cheniere, Eastern Research Group, ExxonMobil, KeyLogic, the National Institute of Clean and Low Carbon Energy (Beijing) and SLR. P.B. has research currently funded by Enagas SA, and the Collaboratory to Advance Methane Science (CAMS). P.B. has acted as consultant for several organizations in the natural gas sector including Cheniere, BP, Shell, Woodside and the Oil and Gas Climate Initiative. P.B. has also been an expert witness or consulted with Friends of the Earth, UK Committee on Climate Change and Cheshire Council West. S.A.R.W., J.A.L., and K.G.F. have worked as consultants for Cheniere, Saudi Aramco, and the National Energy Technology Laboratory. S.A.R.W. is now an independent contractor to Cheniere. J.A.L. is now an employee of Aramco Americas. In the past, J.A.L. has provided consulting services to Underwriters Laboratories. K.E.K. has done work as a consultant for the International Energy Agency.

ACKNOWLEDGMENTS

The authors thank Robert Fee, John Adamo, Iain Mackie, and Guy Nicholls at Cheniere for providing subject matter expertise in this study.

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