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Research Article

Gas Pathing: Improved Greenhouse Gas Emission Estimates of Liquefied Natural Gas Exports through Enhanced Supply Chain Resolution

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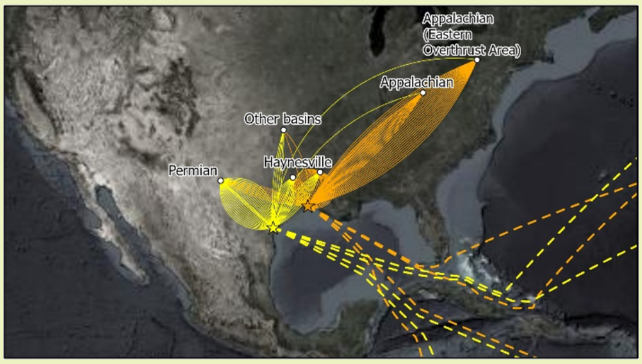
ABSTRACT: The utilization of greenhouse gas (GHG) life cycle assessments (LCAs) of liquefied natural gas (LNG) has increased over the past decade. In this study, a novel framework for improved supply chain-specific LCAs for GHGs is presented using a gas pathing algorithm aligned with how gas is purchased, sold, and transported within the U.S. Utilizing supply chain emissions and gas purchase data specific to two U.S. liquefaction facilities, we identify 138 distinct gas pathways with GHG emission profiles that can vary by nearly a factor of 6. Reference case GHG intensities are 22−53% lower than prior studies for U.S. LNG delivered to Europe (production through regasification, 100-yr GWP). This study also incorporates recent supply chain measurement data. GHG intensities based on measurement data for U.S. LNG delivered to Europe are 41−52% higher than the reference case (production through regasification 100-yr GWP) and 8−11% higher for production through power generation boundaries (all market destinations, 100-yr GWP) but 20−28% lower than prior estimates employing national or regional nonempirical data. Supply chain-specific LCAs and the integration of emission measurements in LCAs are critical to accurately characterize the differences in GHG emissions from natural gas and LNG supply chains.



KEYWORDS: *LNG, natural gas, differentiated gas, LCA, GHG, methane, supply chain, gas pathing*

INTRODUCTION

In 2023, global liquefied natural gas (LNG) exports reached 412 million tonnes (mt), with the United States (U.S.) becoming the largest exporting country and the largest LNG supplier to Europe, accounting for about 48% of imports into the European Union (EU).[1−3] The growth in natural gas and LNG has driven interest in the quantification and mitigation of greenhouse gas (GHG) emissions, especially methane, across the gas supply chains. For example, in 2024, the Biden-Harris Administration paused the processing of LNG export licensing to Non-Free Trade Agreement (FTA) countries to assess the impacts of U.S. LNG exports including associated impacts on GHG emissions.[4] Numerous regulatory and voluntary programs have emerged in the U.S., EU, and Asia that, either explicitly or implicitly, require improved understanding of methane emissions of natural gas supplies.[5,6] Methane rules introduced in the EU will require importers of natural gas to assess the methane intensity of the imported gas.[7]

Currently, the U.S., EU, and more than 15 other countries are working together to develop a global measurement, monitoring, reporting, and verification (MMRV) framework to estimate GHG emissions across the supply chain, including "a transparent and consistent life cycle analysis tool".[7] At the end of 2023, approximately 30% of U.S. natural gas production had been labeled by voluntary certification entities as "Responsibly Sourced" or as "Differentiated" gas.[8] For these voluntary and regulatory efforts to be effective at reducing methane emissions and trusted by the public, they must account for the life cycle of natural gas and LNG supply chains, require credible measure-

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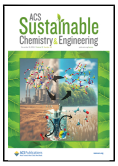

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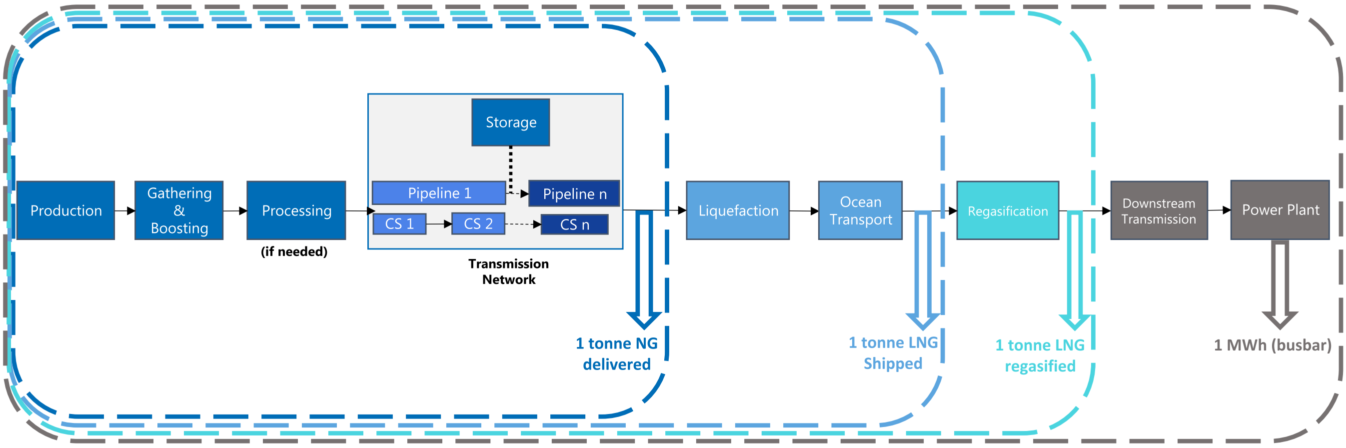

Figure 1. Four functional units examined in this study: 1 tonne of natural gas (NG) delivered to the liquefaction facility, 1 tonne of LNG shipped (landed) in a destination market, 1 tonne of LNG regasified, and 1 MWh of electricity generated from a natural gas-fired power plant [adapted from Roman-White et al.[14]].

ment methods, and report data transparently.[9,10] Life cycle assessment (LCA) models enable relative comparisons of the GHG emissions from different gas supply chains normalized to delivered gas and therefore provide a robust analytical tool to differentiate gas supply chains.[11−14]

Multiple LNG-related LCA studies have been published since 2016, but these studies do not account for the granularity needed for supply chain-specific emission estimates (SI Section S1). Prior work demonstrates that there is significant variability in GHG emissions between operators and across different natural gas supply chains.[11,14−17] NETL (2014, 2019)[11] offers a public model and framework to use U.S. Environmental Protection Agency's (EPA) Greenhouse Gas Reporting Program (GHGRP) data for LCA. Roman-White et al.[14] introduced a framework to develop supplier-specific LCAs that demonstrated the importance of employing supply chain-specific data. While these studies have improved the accuracy and methodologies for LCAs of natural gas supply chains, they provide limited granularity for the midstream (gathering and boosting (G&B), processing, and transmission) segments of the supply chain. Studies have shown that the midstream segments of the value chain can account for over 50% of the total GHG intensity on a production through liquefaction basis.[14,18−20]

To improve the supply chain specificity of LNG LCAs, this study maps how gas is purchased and transported in the U.S. domestic market, employing a combination of data on contracted counterparty capacity and physical flow volumes to develop 138 distinct "gas pathways" from natural gas production to Cheniere's Sabine Pass and Corpus Christi liquefaction plants. This gas pathing improves the spatial resolution of natural gas supply chains in the United States, providing better granularity in the life cycle emissions profile of the production through transmission supply chain, supporting differentiation of natural gas and LNG supplies.[11,14]

■ METHODS

We estimate GHG emissions for the 2022 natural gas supply chains of Cheniere's Sabine Pass Liquefaction (SPL) and Corpus Christi Liquefaction (CCL) facilities, employing the Cheniere LCA model version v2 (CLAM v2), an enhanced version of the supplier-specific model CLAM v1 originally presented in Roman-White et al.[14] Results are presented for four functional units and boundaries: 1 tonne of natural gas arriving at the liquefaction facility gate, 1 tonne of LNG shipped to a destination port, 1 tonne of LNG regasified in the destination country, and 1 megawatt hour (MWh) of electricity generated in a destination country as represented in Figure 1. The study boundary accounts for emissions from the following stages of the natural gas supply chain: production, gathering and boosting (G&B), processing, transmission compression, transmission storage, transmission pipeline, liquefaction, ocean transport, regasification, destination country pipeline transmission (downstream transmission), and end use via power generation. This study is conducted in accordance with the requirements for greenhouse gas quantification under the International Organization for Standardizations (ISO) 14067 standards, and principles of ISO 14040 and 14044.[21−23] Total GHG emissions, reported as an equivalent mass of carbon dioxide (CO_{2e}), are estimated using the IPCC Sixth Assessment Report (AR6) global warming potentials (GWP) for methane and nitrous oxide (N_2O). We present results on a 100-year GWP (CH_4 = 29.8 gCO_2e/gCH_4, N_2O = 273, CO_2 = 1) in the Resultssection and on a 20-year GWP (CH_4 = 82.5, N_2O = 273, CO_2 = 1) in the Supporting Information (SI Section S12). A data quality index (DQI) matrix is created for this LCA model to qualitatively characterize uncertainty in the life cycle data utilized and is explained further in the SI (Section S7).[24]

CLAM v2 includes key improvements to the LNG GHG LCA framework: (1) a new methodology to determine the estimated pathway by which gas travels from the producing region to the liquefaction plant (Gas Pathing Algorithm), (2) improved modeling of fuel consumptions via the incorporation of EPA GHGRP Subpart C data, and (3) improvements in modeling free-on-board (FOB) LNG cargos, incorporating data on direct fuel consumptions for the prior ballast leg. Of these improvements, the gas pathing methodology is the most substantial enhancement in model methodology, though all enhance the accuracy of the LCA result. The next sections summarize each of these improvements, and a more detailed description is available in the SI (Table S1, Sections S4 and S5).

Gas Pathing Algorithm. In the U.S., natural gas from production fields is gathered, processed if needed, and transported through intrastate and interstate pipeline networks. Industrial customers purchase gas from known producers and gas marketers (nonproducing entities) at multiple purchase points (locations). Typically, a producer contracts for gathering as well as processing or treating with a gathering entity (or occasionally more than one) that handles its field gas from the wellhead to a processing/treating plant (or in some cases directly to a transmission pipeline) and with a processing or treating entity that will deliver pipeline quality gas into a transmission system. From that point, the producer may have a transportation contract(s) with one or more pipeline transmission systems to deliver the gas to a point of sale, or they may elect to sell gas immediately upon entering the transmission grid to a marketer or consumer such as Cheniere. It is also common for a producer to sell gas to the midstream company that gathers or processes their gas, and they would, in turn, transport or sell the gas. From the

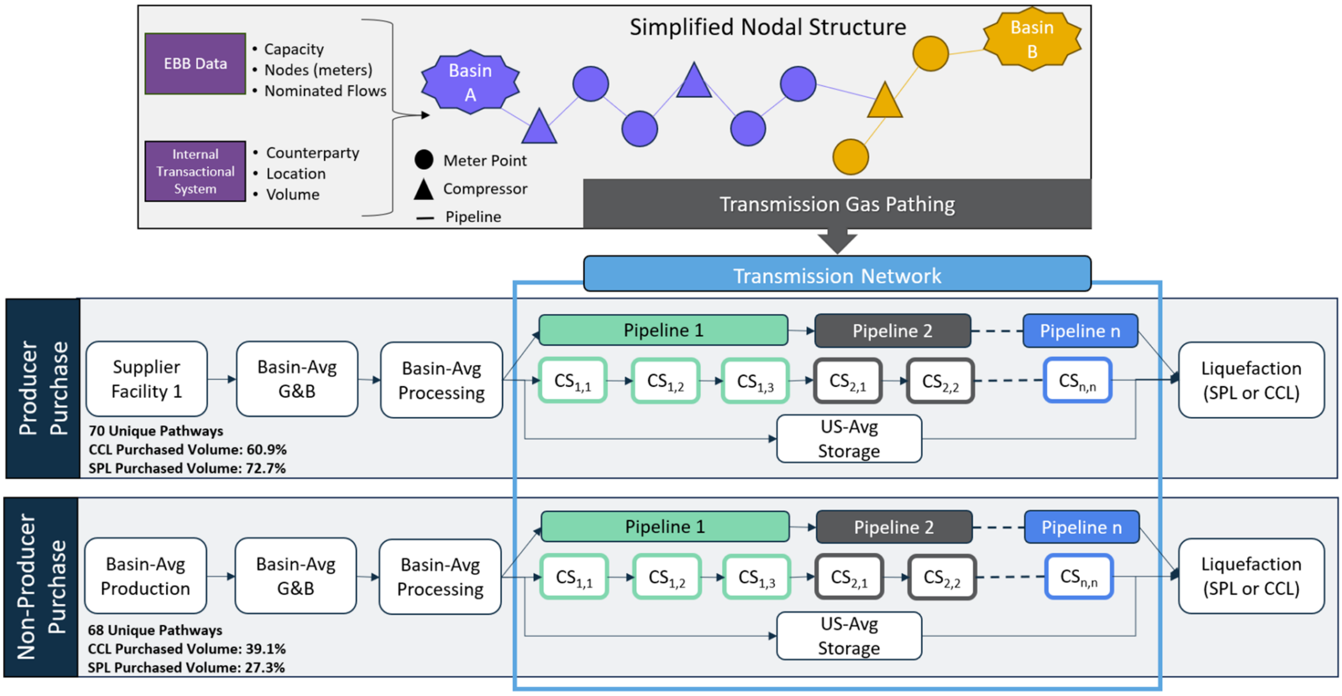

Figure 2. For each counterparty purchase, one or more unique upstream gas pathways are estimated. A unique pathway is determined by the algorithm-estimated pairing of a specific producer (or basin average for nonproducer counterparties) with a unique set of transmission compression stations and pipeline mileages traversed. For all pathways, basin average emission profiles are used as proxies when the exact facility is unknown or emissions data are unavailable. In total, 70 and 68 unique gas transmission pathways are identified using this algorithm for purchases from a producer and a nonproducer counterparty, respectively.

point of purchase, the gas purchaser is responsible for contracting for pipeline capacity to move this gas to its facilities or other points of sale. Regardless of where the gas is sold, it is likely to travel through multiple gas pipeline systems composed of many compressor stations before it reaches a liquefaction plant or other end user.

Developing the transmission network portion of the gas pathway is the most complex part of the algorithm. The gas pathing algorithm used in this work has unique approaches to estimate gas pathways for gas purchased from known producers versus gas purchased from nonproducer counterparties. In both cases, contracted gas volumes are paired with gas transportation data. The key difference in the methodologies is how the portion of the pathway between the gas production region and Cheniere's purchase point is treated. When the counterparty is a known producer, data on the transport capacity held by that producer are known and modeled. When the counterparty is a nonproducer, a mass balance approach is taken using pipeline flow data to trace the net major flows of gas back to a producing region or regions. These gas flows are connected with throughput and emissions data (primarily from the EPA's GHGRP) for relevant facilities to assess the gas pathway emissions from the relevant upstream (production through transmission) supply source to Cheniere's liquefaction plants. The process to develop a production through the liquefaction gas pathway is summarized in Figure 2.

Where the seller of the gas is a producer, the algorithm takes publicly available data related to the transportation capacity held by the producer paired with the purchase points for the underlying transactions and data on Cheniere's held transportation capacity to assess the likely transportation gas pathway for the purchased gas (from production basin to purchase point to receiving liquefaction plant), including the relevant compressor stations contributing to the overall emissions profile of the pathway. For example, Cheniere holds capacity on Columbia Gulf Transmission (CGT) between the Mainline Pool market and its interconnect with Kinder Morgan Louisiana Pipeline (KMLP), as well as capacity on KMLP from the interconnect to delivery at SPL. The same exercise is performed on the pipeline capacity held by the producer counterparty for a given purchase, examining the pipelines between the production basin and purchase point. Thus, for gas purchased as the CGT Mainline Pool point, the transmission gas pathway would consist of all of the pipeline miles and compressor stations between Mainline Pool and delivery to SPL on CGT and KMLP, as well as the compressor stations and pipeline miles traversed on the producer's capacity held upstream of the purchase point.

For nonproducer counterparties, we combine information on Cheniere's contracted transportation capacity downstream from the applicable purchase points (same approach as with producing counterparties) with physical gas flow data from the various transporters' publicly available EBBs, which is aggregated by Wood Mackenzie,[25] to estimate the reasonable gas transportation pathway(s) between the producing basin and purchase point. Thus, if Cheniere purchased from a nonproducer counterparty at Mainline Pool, the transmission gas pathway would look the same from Mainline Pool to SPL delivery as it is still based on Cheniere's capacity. However, the portion of the pathway between the production basin and purchase point would be based on physical flows, mathematically solving for net flows on the pipelines upstream of the purchase point. For 2022, this analysis showed that physical flows from both Columbia Gas Transmission (TCO) and Texas Eastern Transmission (TETCO) systems within the proximity of the production regions flowed into CGT toward Mainline Pool, resulting in multiple pathways related to this purchase point. When the algorithm produces multiple pathways for a nonproducer counterparty, each pathway is weighted based on the ratio of estimated net flows from each pathway flowing into the receipt point (often a pooling location).

When gas is purchased from a nonproducer counterparty, the model is unable to determine the specific producer (operator), and thus there is no data available on specific transportation capacity held between producing basin and purchase point. In this instance, the gas pathing algorithm estimates the probable production basin (or basins) in which the purchased gas originated through the tracing of the physical flow data from the pipelines back to one (or more) producing regions. For nonproducer pathways, a basin average production emissions profile is modeled for the basin identified by the pathing algorithm.

Due to data limitations, the algorithm is limited in identifying individual gathering facilities or individual processing facilities in the way that it does for transmission network pipeline and compression facilities. The algorithm does identify if natural gas entered the transmission network from the tailgate of a processing facility or from the connection of a gathering system. Thus, we employ basin average emission profiles as derived from the EPA GHGRP for gathering and (where identified as part of the pathway) processing operations. The gas pathing algorithm is described in more detail in the SI (Section S4.4).

The gas pathing algorithm is a major enhancement in how CLAM represents supplier-specific supply chains. CLAM v1[14] represented only a single average supply chain consisting of average emission profiles across all identified gas suppliers in the supply chain. High-level assumptions were used to estimate the miles of the pipeline and number of compressor stations. With CLAM v2, specific compressor stations and miles of pipeline are modeled along the likely gas pathway from the production basins to the liquefaction plants based on the counterparty and purchase location. Further, these pathways are weighted based on the volume of gas purchased on a given pathway, giving a more accurate understanding of Cheniere's supply mix feeding into the liquefaction facilities.

Combustion Sources Improvements. Combustion sources are a significant contributor to life cycle emissions in the upstream natural gas supply chain,[14,26] particularly in the G&B, processing, and transmission compression stages of the supply chain. In CLAM v2, we employ activity data extracted from GHGRP's Subpart C reporting.[27] This data set provides directly the quantities of fuels combusted in each type of equipment, removing any assumptions on driver efficiency to estimate fuel consumption (as was done in CLAM v1[14]). This implementation is described further in SI Section S4.3.

Ocean Transport Model Improvements. CLAM v2 model represents each voyage as traversed, meaning a round trip assumption is no longer used (CLAM v1 assumption) and the laden and ballast legs are modeled as they occurred in 2022. CLAM v2 employs vessel-specific fuel consumption guarantees as well as a "scale-up" factor to account for the ideal operating condition assumption in the vessel guarantee data. Our analysis found the ideal operating assumptions, used for specific performance guarantees in Form B, defined as the "Particulars of the Vessel", underestimate actual fuel consumption by 18.5% on average. This analysis forms the basis for the scale-up factor of 1.185. This factor and other improvements in the Ocean Transport data inputs and unit processes relative to CLAM v1[14] are explained in detail in the SI (Section S5.2).

Model Data Sources—Reference Case (RC). The reference case in this study employs activity and emissions data from the EPA's 2022 GHGRP Subpart C and Subpart W for the production through liquefaction segments of the supply chain, augmented with data collected from Cheniere's upstream supply chain for sources and facilities not reported to the GHGRP (when provided by the supplier), along with ocean transport data as outlined earlier and in SI Section S5.1. Where the data were not available from the supplier or EPA, a proxy profile based on EPA data for the given stage and basin (for production through processing) was developed. EPA data proxy profiles were created via statistical bootstrapping to estimate distributions of the average value for each available parameter. A unique average profile was created for each defined basin for production, G&B, and processing, and a single average profile for the transmission segments of the supply chain. Statistical methods for proxy profile creation are further explained in the SI (Section S2).

Liquefaction stage GHGRP emissions for SPL and CCL are augmented with CO_2 estimates for the acid gas removal unit, additional methane sources, and electricity consumption and related emissions (see SI Section S4.5 for details).

Ocean transport emissions were estimated for 498 individual cargoes loaded at SPL or CCL in 2022, employing vessel-specific details based on Voyage Logs, independent Cargo Survey reports, Particulars of the Vessel (Form B) documentation, and IHS Markit's maritime data (see SI Section S5 for a detailed discussion on data sources and methodology).

Regasification, downstream transmission, and power generation unit processes are modeled based on prior work in Roman-White[14] that derived estimates from published literature, third-party data sets, and engineering calculations, further detailed in SI Section S6. However, end use efficiencies are updated to reflect 2022 vintage information based on latest data from the IEA,[28] incorporating electricity generation from both power plants and combined heat and power (CHP) plants to estimate an average effective electricity generation efficiency for each market destination.

Model Data Sources—Measurement-Informed Case (MC). Multiple studies have shown that empirical or measurement-informed inventories are higher than inventories developed using activity-based methods.[29−37] Incorporation of direct measurement data into LCAs is a critical next step to improving the accuracy and usability of such models, and discussed in a recent study.[12] However, data published via measurement campaigns at oil and gas facilities generally lack the granular facility or process-level data on source/equipment attribution and product flows necessary to incorporate into an LCA framework.[10,12] Demonstrations of how measurements can be used to refine life cycle inventories have been published in other studies.[12,17] SI Section S11 summarizes methane emission rates from recent upstream measurement studies at various basins.[38]

Limited measurement data are available to represent in detail Cheniere's specific supply chain upstream of the liquefaction facilities. Thus, to present an indicative measurement-informed case study using CLAM v2, we incorporate Lu et al.'s[39] analysis of 2019 vintage measurement data from a satellite campaign across the U.S. as a proxy to adjust the modeled upstream methane emissions for the production through transmission segments. For the Montney basin in Canada, recent work from Johnson et al.[40] is used to represent methane emissions intensity for gas procured from Canada (production through transmission). In addition to this scaled measurement factor for upstream emissions for the measurement-informed case, we employ recent methane measurement data from a 16-month measurement campaign performed in 2022−2023 at SPL and CCL from Zhu et al.[17] and continuous emissions monitoring data from a sample of Cheniere chartered LNG vessels, in lieu of input data from GHGRP and other engineering estimation methods, to provide an indicative measurement-informed case GHG life cycle estimate.

Lu et al.[39] provided wide geographic coverage of U.S. operations consistent with the production basins and gas pathing boundary studied in this work. Further, the study published additional data (production flows and gas-to-oil ratios) to support coarse integration into the LCA framework. We note, however, that the estimates from Lu et al.[39] may differ from other measurement-informed inventories (Table S25). For example, Lu et al.[39] report that mean US methane emission intensities (methane emissions divided by gas produced) decreased from 3.7% in 2010 to 2.5% in 2019. In contrast, other recent measurement studies present methane intensities for different U.S. basins ranging from 0.13 to 9.4%, employing various measurement techniques for temporal periods researched in their respective work. Also, a synthesis study from Alvarez et al.[35] estimated a mean U.S. methane emission intensity of 2.3% for data collected between approximately 2013 and 2016. We scale up methane emissions by a factor that represents the average difference between reference case modeled inventories and top-down measurements.[39] See SI Section S11 for further details.

Therefore, the reference case emissions data primarily relies on bottom-up, activity-based estimates for specific sites in each stage of the gas pathway for calendar year 2022, representing a granular understanding of Cheniere's specific supply chain life cycle emissions, though limited by the underlying data source as discussed above The measurement-informed case provides an assessment of the impact of higher methane emissions from the production through shipping stages to the total life cycle emissions intensity but is less specific to Cheniere's supply chain, limited to a regional understanding of the upstream.

Studies have shown it is important to understand the quality of data inputs to evaluate life cycle inventories.[41] We employ the EPA's Data Quality Indicators (DQI)[24] to qualitatively evaluate the data inputs in our model (SI Section S7). Further, studies have shown that harmonization of results is an important step to allow for better comparability of LCAs.[12,42,43] Lack of harmonized inputs, boundaries, assumptions, etc. can lead to significant variation in reported LCA

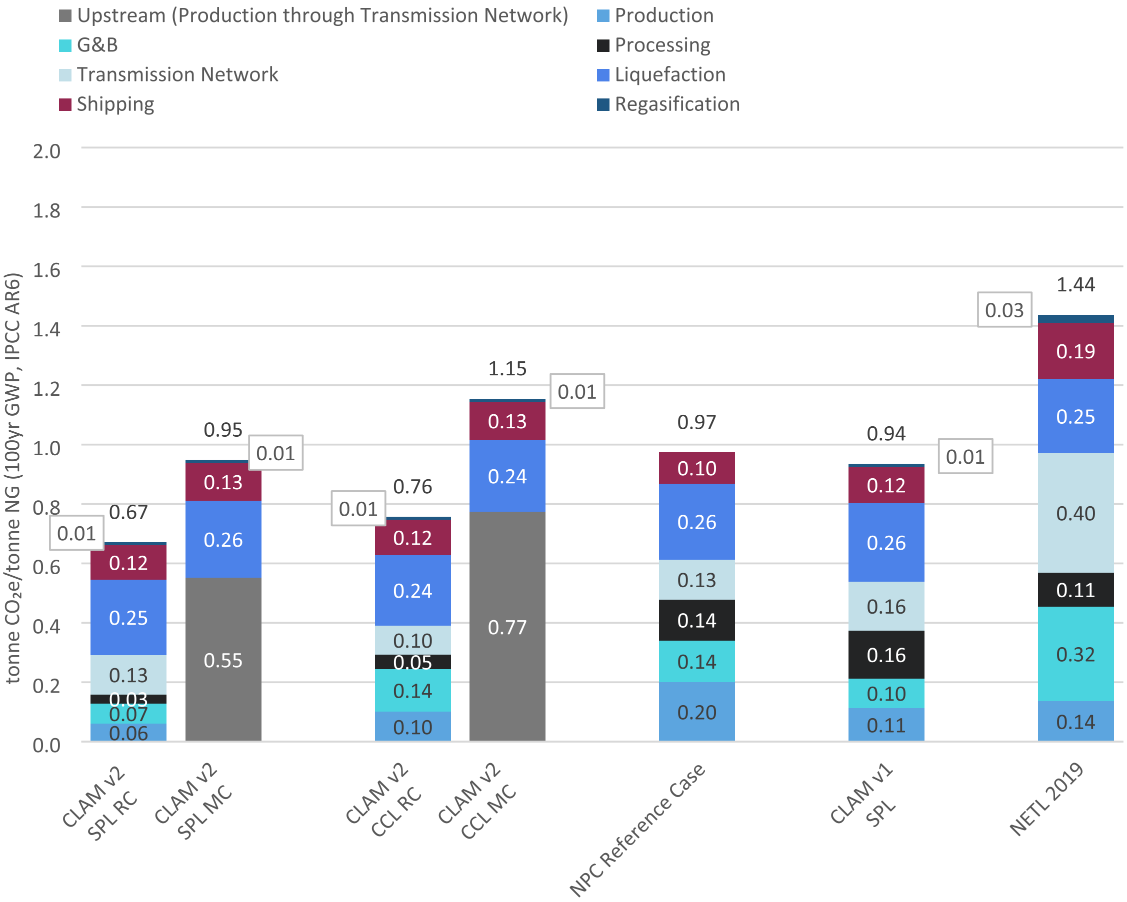

Figure 3. GHG emission intensity from production through regasification for CLAM v2 RC, CLAM v2MC (both data vintage 2022), compared to results from CLAM v1 (2018 data vintage[14]), NPC study SliNG-GHG model (2016−2022 data vintage), and NETL 2019 LNG study (data vintage 2016). The CLAM v2 results represent the weighted average portfolio of all pathways estimated to have delivered to SPL and CCL in 2022, weighted by the gas purchased on each pathway. All results were harmonized to AR6. The NPC result is only produced through ocean transport, although as evidenced by the other results presented, regasification emissions are relatively insignificant. The gray color used to represent the upstream (production through transmission) in the MC accounts for all GHG species (i.e., CO_2, CH_4, and N_2O). It is directly comparable to the production through transmission network stages shown stacked in the RC. The MC upstream is shown as an aggregated block due to the coarser granularity of the methane data employed in the MC. The (generally) increased methane emissions from the upstream under the MC lead to increased overall CO_2e intensity relative to the RC result.

results. Granular harmonization of results is beyond the scope of this study. We have attempted to align on boundary, geography, and GWP when comparing LCA results from CLAM v2 to other models.

■ RESULTS

Figure 3 presents the reference case (RC) and measurement-informed case (MC) GHG emission intensity results for SPL and CCL weighted average supply chain volumes (2022 gas purchasing) on production through regasification basis for LNG delivered to the European Union and the United Kingdom. Two liquefaction facilities with similar technology in the Gulf Coast, owned and operated by the same company, exhibit different life cycle emission profiles because of the different upstream supply chains delivering gas to the plants. SPL and CCL have significantly different gas supply portfolios for 2022. SPL sourced a significant amount of “dry gas” from the Appalachian basin, driving lower emissions intensity on average from the production and processing stages, but SPL gas pathways had on average a higher transmission network emissions intensity relative to CCL. CCL purchased a significant amount of gas from the Permian, which supports the lower average transmission emissions intensity for CCL.

Further, while production is an important segment of the supply chain, it accounts for only 9−13% of emissions in the reference case (100-year GWP production through regasification, SPL, and CCL, respectively), whereas the midstream segments of the supply chain collectively account for 34−38% of the emissions at SPL and CCL, respectively. While these trends are observed in the average emissions profile for each facility, there is significant variability in the emissions intensity of an individual pathway and the stagewise contribution analysis, even for pathways sourcing gas from the same basin and delivering to the same liquefaction plant.

A contribution analysis of the measurement case results shows the increased emissions from the upstream segments (production through transmission) relative to the reference case for the production through regasification boundaries. The upstream emissions contribute 43−52% of emissions in the RC for SPL and CCL exports, respectively, which increases to 58−67% in the MC, while contribution from the liquefaction and shipping stages decreases (100-year GWP).

Figure 3 also compares the results from CLAM version 2 to other published estimates: CLAM v1 results published in Roman-White et al. 2021 (UK average),[14] NETL 2019[20] LNG

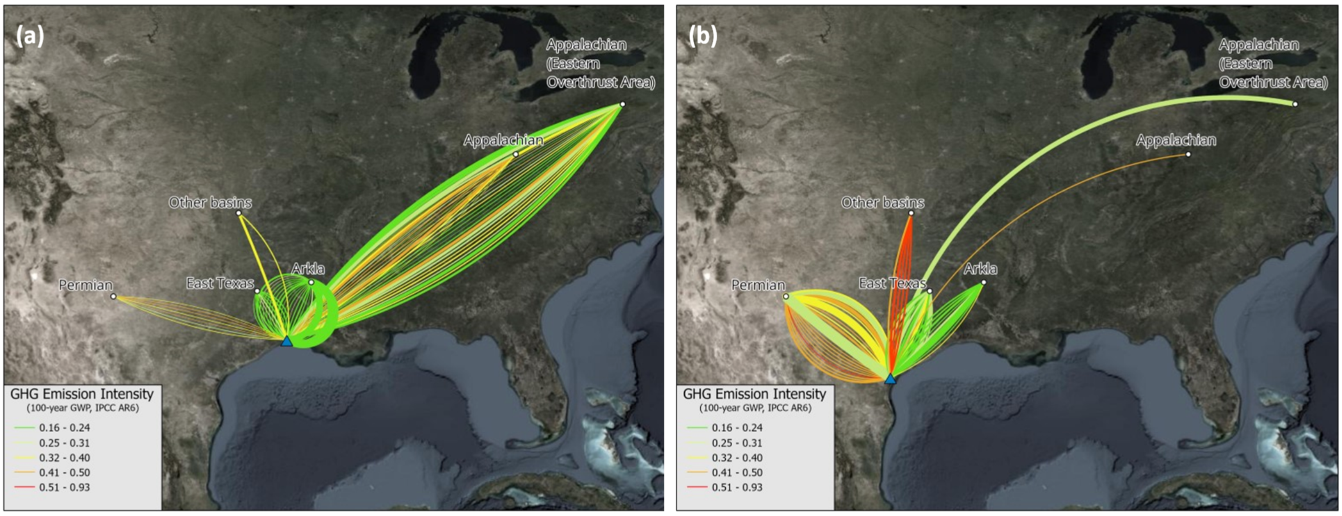

Figure 4. Simplified gas pathing visualization, where each line is an individual gas pathway identified as relevant for Cheniere in 2022. These pathways comprise only the pathways identified via gas pathing to serve Cheniere's liquefaction facilities in the study year; they do not represent a "basin average" understanding of all gas operations in these regions. In 2022, over 10% of the gas (dry) produced in the U.S. was exported as LNG. Each line starts in the estimated production basin and connects to the relevant liquefaction plant. Panel (a) shows pathways relevant to SPL, and panel (b) shows pathways relevant to CCL. The width of the line is representative of the relative pathway "weight" for that pathway, which is what percent of gas purchased in 2022 was estimated to have arrived from the gas pathway. The color of the line is indicative of relative GHG emissions intensity, with green lines having lower emissions intensity and red lines having higher emissions intensity, with nearly 6× variation relative to all gas pathways for Cheniere. The lines are illustrative and do not trace the actual individually pathed pipelines to preserve data confidentiality. Pathways labeled as "Other basins" are only a graphical representation of pathways sourced from basins that did not have a substantial number of total pathways to protect data confidentiality. Other basins pathways are not indicative of the actual location of the basin.

study results (Netherlands case study), and the NPC Charting the Course SLiNG-GHG[12] model results (Europe case study). The SLiNG-GHG model is a publicly available streamlined LCA model for screening-level estimates, developed to focus on key sources of GHG emissions across the natural gas supply chain. These results have not been harmonized beyond employing the same GWP values.

GHG emissions intensity from the CLAM v2 SPL RC is about 28−37% lower than CLAM v1 2018 data for deliveries to Europe and Asia, respectively (100-year GWP, see SI Figure S28 for comparison with Asian market LNG delivery). The CLAM v2 RC results for SPL and CCL are 47−53% lower than the NETL study, and 22−31% lower than the NPC study (100-year GWP). Results from the CLAM v2MC are 20−34% less intense than the NETL study and 2% lower to 19% higher relative to the NPC study. The 2018 CLAM v1 and CLAM v2 SPL MC are comparable for exports to Europe.

The comparison illustrates the significant difference in results from CLAM version 2 relative to other models. This is likely driven by a combination of differences in study data vintage and supply chain representation (i.e., the introduction of gas pathing). The impacts of data vintage and supply chain representation are explored further below on the production through the transmission network boundary.

Figure 4 illustrates the variability in GHG emissions intensity of individual gas pathways on production through a transmission network basis. Each line represents a unique gas pathway modeled for Cheniere's 2022 supply chain, starting in the production basin and connecting to the relevant liquefaction plant. There is notable variability in emissions intensity not only for pathways sourcing gas from different basins, but for distinct pathways originating in the same gas production basin. Prior studies have illustrated intrabasin emissions variability among producers using both engineering and measurement-informed methods.[32,44−46] Similarly, variability in emissions profiles has been observed in the transmission segment.[11,47−51] These occur due to differences in prime-mover design and horsepower capacities at compressor stations, and operational and temporal variability in compressor station operations.[11,47−49,52]

The combination of differences in emissions at production and midstream facilities along each gas pathway results in variation in life cycle emissions between gas pathways, including pathways originating in the same production basin. The highest individual gas pathway emissions intensity of 0.93 tonne CO_2e/tonne NG is nearly 6× that of the lowest emission intensity gas pathway 0.16 tonne CO_2e/tonne (100-year GWP, production through transmission). Even for gas pathways sourcing gas from the same basin and delivering it to the same liquefaction facility, pathways varied as much as 99% (see SI Section S9 and SI Figure S26). This variability demonstrates the importance of incorporating supplier-specific data into LCA models. A detailed comparison of basin average pathway emissions intensity is presented in SI Figure S26, comparing reference case and measurement case results from CLAM v2 along with comparable results from the published NPC study SliNG-GHG model,[12] as well as results run with 2022 data vintage using the publicly available NETL model.[26]

To assess the impact of the gas pathing framework against generic, national estimates, we ran a hypothetical U.S. average supply chain in CLAM v2, assuming U.S. average emissions intensity from EPA GHGRP 2022, and, consistent with NETL 2019,[11] assuming on average 90% of gas goes through gathering and boosting, 75% is processed, and all travels through 10 compressor stations and 600 miles of pipeline. CLAM v2 gas pathing weighted average emissions intensity is 9−33% lower (CCL and SPL) versus a hypothetical U.S. average simulated in CLAM v2 without gas pathing, production through a transmission network basis (see SI Figure S20). To provide a relative

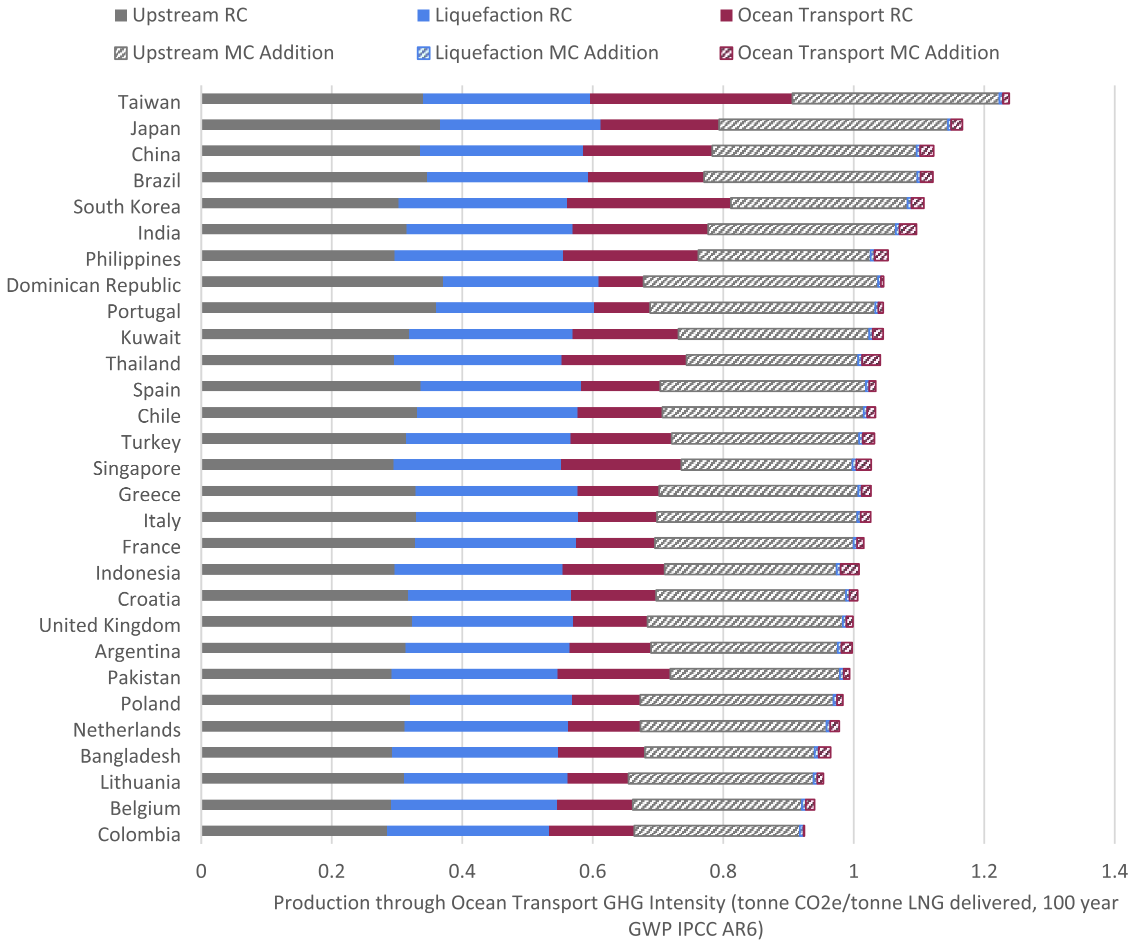

Figure 5. Production through ocean transport emissions intensity by market destination, weighted average based on volume of LNG delivered, combined for all cargoes loaded at SPL and CCL in 2022. Reference case 100-year GWP intensity shown as the first 3 stacks, color-coded in bold color fill. The measurement case results are shown as relative increases stacked on top as an adder, represented by the hashed portion of the bar. Each stage has the same color outline (gray, upstream; blue, Liquefaction; Red—Ocean Transport). To interpret the measurement case result for a given stage, it is the sum of the intensity shown in the reference case plus the adder shown for the measurement case.

comparison point controlling for data vintage, we input GHGRP 2022 data into the NETL 2019 public model (see SI Section S10 for more details).

We find that the production through transmission network GHG intensity from CLAM v2 is 43−58% lower than the NETL results (public model rerun with 2022 data vintage, 100-year GWP), comparing the SPL and CCL weighted average reference case to the NETL national average scenario (see SI Figure S20 for comparison, as well as SI Figure S26 for a basin-by-basin comparison). Thus, while we are unable to explicitly disentangle the drivers of differing results from CLAM v1, CLAM v2, and other LCA models due to limitations in the model input data and overall structure, we can conclude that the gas pathing algorithm presented in this work represents improved characterization of the supply chain emissions.

Figure 5 expands the life cycle boundary to the ocean transport stage, summarizing results for combined Cheniere (SPL and CCL) average cargo emissions intensity by market destination, weighted based on the volume of LNG delivered, showing both the reference case and measurement case results. The MC results are on average 36−54% higher than the reference case for the production through shipping boundaries for a range of all market destinations using a 100-year GWP.

Figure 6 shows the production through the end use life cycle boundary, modeling power generation as the assumed end use. GHG reference case intensities range from 392 to 610 kg CO_2e/MWh (busbar) on a country average basis (100-year GWP), with end use combustion the largest contributor to overall emissions. This holds true in the measurement case, where emissions increase to range from 422 to 671 kg of CO_2e/MWh, but end use remains the highest contributing individual stage. When the end use stage involves combustion, efficiency is the largest driver of emissions. On the production through ocean transport basis, Singapore had an average emissions intensity 11% higher than Belgium. However, on the production through power generation basis, that difference shrinks to less than 4% due to the significant contribution of emissions from end use combustion. While Singapore is located much further away from the Gulf Coast than Belgium, Singapore had an average effective natural gas power plant efficiency of 56.3% (higher heating value) in 2022, almost as high as Belgium's average effective natural gas power plant efficiency of 57.2%. The MC results are 8−11% higher than the RC on a 100-year GWP basis, but MC results are 20−28% lower than LCA GHG intensities presented in the NETL 2019 study for the production through power plant boundary (100-yr and 20-yr GWP range) (SI Figure S31).

Implications. This work has demonstrated that there is significant variation between gas pathways connecting production basins to consumers, such as liquefaction plants. This variation exists even within the gas pathways originating from

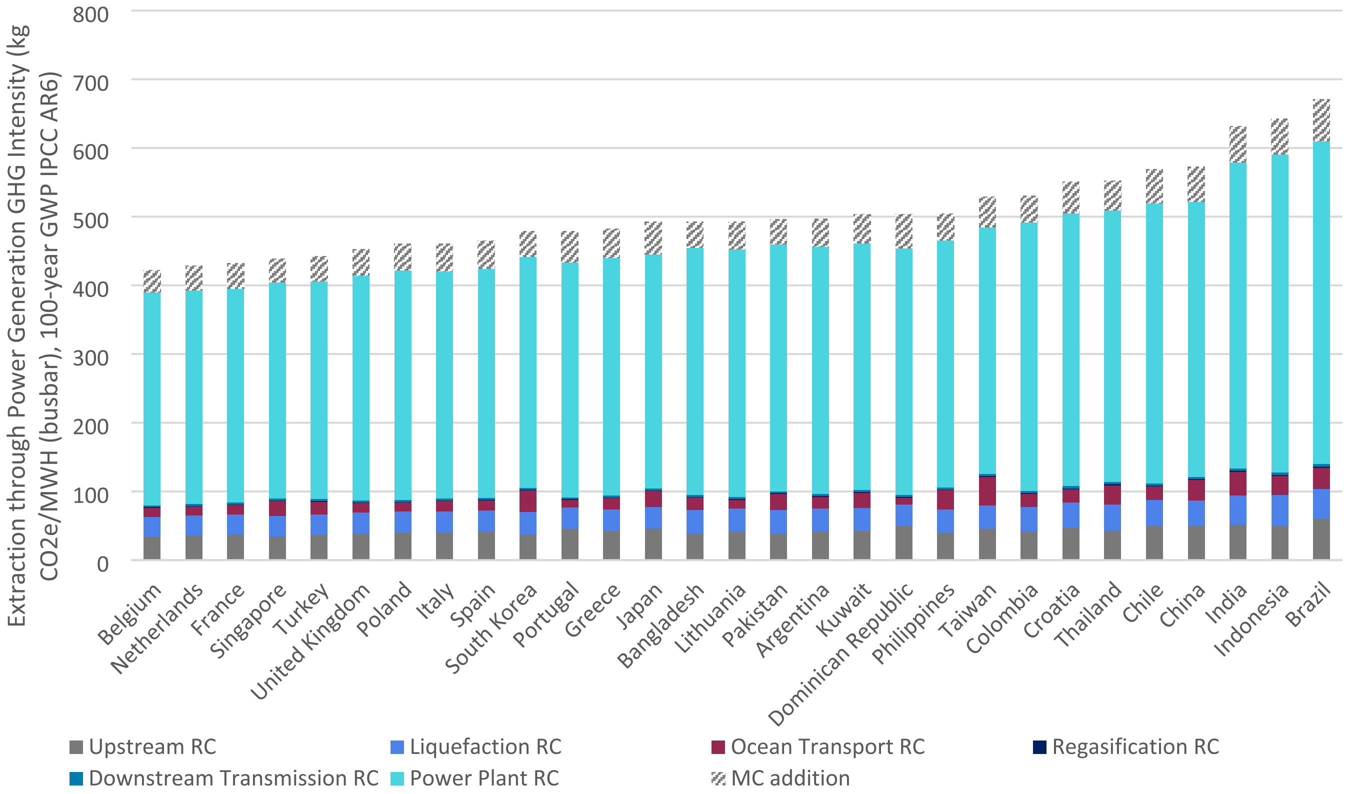

Figure 6. GHG emissions intensity for the production through power generation supply chain, weighted average of all SPL and CCL cargoes for 2022. Power generation in each country is modeled based on the calculated average effective natural gas power plant efficiency in each market destination. This effective efficiency is derived from information about both electricity and CHP plants. End use (combustion) is the single largest contributor to the overall life cycle emissions in both RC and MC.

the same basin. Supply chain-specific LCAs can be a powerful tool to support natural gas and LNG supply differentiation by providing the emissions profile of the delivered product through a detailed estimation of the emissions from each segment of the supply chain. The recently finalized methane rules in the E.U. require information on methane emissions from producers and exporters of LNG placed on the Union market, including information on the methane intensity associated with the production of natural gas. This work represents natural gas supply chains in a manner that aligns with how gas is sold and transported in the U.S. market, reviewing physical and contracted volumes of gas through the pipeline network and constraining a finite set of gas pathways to physical limitations like capacity and pipeline interconnects. The LCA framework presented in this study enables LNG exporters to reasonably identify and model GHG emissions from known producers and nonproducer counterparties in specific production regions and facilities along the gas pathway.

While the novel algorithm demonstrated here employs the best available data on gas purchases, firm transport capacity, and scheduled gas flows, the U.S. natural gas supply chain is vast and complex. Natural gas molecules cannot be tagged or traced within the network. There is no guarantee that the contracted molecules from a specific producer or operator are the ones that ultimately show up at the purchase point.

Going forward, future enhancements in gas pathing should focus on identifying individual gathering systems and processing plants to further refine and improve GHG estimates. We contend that similar to other contracting mechanisms such as power purchase agreements (PPAs), proof that individual molecules (or power flow in the case of PPAs) arrived at a delivery point may not be required for robust differentiated gas. Rather, an approach aligned with the principles of the framework presented here may be required, in which the linking of a gas purchase with a gas pathway tied to physical infrastructure and facility-specific emission profiles is repeatable and links the new natural gas supply to the ultimate consumer.

Incorporation of measurement data into LCA models is important to provide stakeholders greater confidence in claims made by suppliers on GHG intensities of their delivered product. Most measurement studies have not presented data in a format compatible with LCA models such as CLAM v2 or NETL 2019. Data must be at the appropriate spatial (facility level) and temporal (multiple measurements to account for variability) scale and published alongside sufficient relevant data to support partitioning or allocating emissions consistent with ISO standards.[22,23] Therefore, integrating measurement data, including associated uncertainties, into detailed LCA model structures is challenging, and best practice recommendations regarding the combination of measurement instruments and data analysis are under development. These best practices must also incorporate uncertainties in direct measurement methodologies and translate that uncertainty into the overall life cycle inventory. In this work, we provide an assessment of input data quality via a Data Quality Index, but future work should aim to produce uncertainty bounds around the LCA result. The state of science continues to rapidly evolve for GHG measurement technologies; beyond just detecting emissions, there are a number of steps needed to arrive at a quantified rate. As noted by Brown et al.,[53] there can be wide divergence in facility-level estimates contemporaneously measured by different measurement technologies. As measurement technologies improve their detection and quantification methods, including uncertainties, operators can employ the results along with other data to develop more robust site-level empirical estimates which then can be incorporated into life cycle inventories, after appropriate spatial and temporal boundary matching, coallocation, and other methodological steps required in LCAs.

The measurement-informed case presented here can only provide indicative emissions and directional comparisons with process-based LCA results, as in the reference case presented in this work. Incorporation at-scale of directly measured emissions data for all stages of the supply chain is needed to best inform the development of appropriate mitigation strategies. Harmonization of LCA studies (scope, boundary, metrics, etc.) and assessment of overall data quality employed in LCAs are important to compare LCA results from different studies in a consistent manner.

Finally, registries that record the environmental attributes of natural gas have been recently established to foster the sale of differentiated gas: either the gas molecules (i.e., on a bundled basis) or their (lower) methane intensity attributes (i.e., selling the attributes unbundled from the gas itself). Although such registries have to date concentrated on the emissions profile of production operations, they are flexible by design and can accommodate specific pathways across the supply chain as considered in this analysis (SI Section S13). However, given the nascency of these gas registries, additional research linking the framework and algorithm for natural gas LCAs presented here into these ledger technologies is recommended to enable monitoring and verification to support regulatory reporting, differentiation, and commoditization of natural gas across the supply chain.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.4c07162.

Unit process structure and calculations (ZIP)

Parameter documentation and default values (XLSX)

Reference case base emissions (XLSX)

Blinded pathways (XLSX)

Additional details regarding data sources, calculation methods, and data quality assessments (PDF)

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The authors declare the following competing financial interest(s): F.C.G., G.R., and D.M.P. are currently employees of Cheniere Energy Inc. S.A.R.-W. was an employee of Cheniere until May 2024 and is currently an employee of SLR International, which performs work for Cheniere, other oil and gas industry clients, academic institutions, and industry research organizations. A.M. is an employee of Rystad Energy, an energy research and intelligence company. D.T.A. serves on the Science Advisory Board of the U.S. Environmental Protection Agency, in which role he is a paid Special Governmental Employee; his research is currently supported by the National Science Foundation, the Department of Energy, the Texas Commission on Environmental Quality, Chevron, ExxonMobil, Pioneer Natural Resources, and the Environmental Defense Fund, and he has also worked on air quality projects that have been supported by oil and gas producers and the Environmental Defense Fund; he has worked as a consultant for multiple companies, including British Petroleum, Cheniere, Eastern Research Group, KeyLogic, and SLR International. A.P.R. has current research support from multiple natural gas producers and the Environmental Defense Fund and has worked as a consultant for SLR in recent years. 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, and has also been an expert witness or consulted with Friends of the Earth, UK Committee on Climate Change, and Cheshire Council West. M.B. and B.H have current research support from Cheniere. H.K. and K.C. are employees of KeyLogic, which has provided consulting support to the National Energy Technology Laboratory, Cheniere, and Saudi Aramco.

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