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Letter

Multiscale Measurements of Greenhouse Gas Emissions at U.S. Natural Gas Liquefaction Terminals

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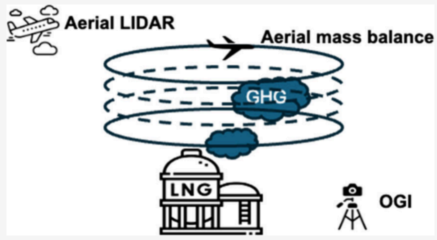

ABSTRACT: Addressing methane emissions across the liquefied natural gas (LNG) supply chain is key to reducing climate impacts of LNG. Actions to address methane emissions have emphasized the importance of the use of measurement-informed emissions inventories given the systematic underestimation in official greenhouse gas (GHG) emission inventories. Despite significant progress in field measurements of GHG emissions across the natural gas supply chain, no detailed measurements at US liquefaction terminals are publicly available. In this work, we conduct multiscale, periodic measurements of methane and carbon dioxide emissions at two US LNG terminals over a 16-month campaign. We find that methane emission intensity varied from 0.007% to 0.045%, normalized to methane in LNG production. Carbon dioxide emissions accounted for over 95% of total GHG emissions using 100-year global warming potential (GWP) for methane. Thus, contrary to observations across other natural gas supply chain segments, we find that reported GHG emissions intensity closely matches measurement informed GHG emissions intensity of 0.24−0.27 kg CO_2e/kg CH_4. In the context of developing LNG supply chain emissions intensity, we conclude that the use of the Greenhouse Gas Reporting Program emissions intensity provides reasonably accurate estimates of total GHG emissions at LNG terminals.

KEYWORDS: *Methane emissions, Measurement-informed inventory, LNG, Supply chain, Climate impacts*

1. INTRODUCTION

Global demand for liquefied natural gas (LNG) is expected to grow in the future with US LNG export capacity increasing by 18% by 2025.[1,2] This has raised significant concerns about its climate impact, and further underscored by increased demand for non-Russian sources of natural gas in Europe.[3−6] The US Department of Energy (DoE) has temporarily paused review of new LNG export applications in part to update prior analysis of the climate impacts of US LNG.[7] With a global warming potential 84 times that of carbon dioxide over a 20-year period, methane emissions along the LNG supply chain are a key component of climate impacts of LNG.[8] Recent research has demonstrated that methane emissions account for 47% of supply chain GHG emissions under a 20-year GWP basis, and methane leakage over 4% threatens to erode the climate benefits of natural gas over coal.[9−11] Thus, addressing methane emissions across the natural gas supply chain is a key component of near-term action to reduce climate impacts of LNG.[12]

Measurements of methane emissions across the oil and gas supply chain have identified systematic underestimation in official GHG emissions inventories.[13−16] Global efforts to address methane emissions from the LNG supply chain have emphasized the importance of the use of measurement-informed emissions inventories.[17−20] The European Commission finalized methane regulations that set measurement and reporting requirements for natural gas and LNG imported into the EU market.[21] Several voluntary initiatives, including the US DoE's Measurement, Monitoring, Reporting, and Verification (MMRV) framework and the Oil & Gas Methane Partnership (OGMP) 2.0, propose to establish accurate and transparent emission reporting frameworks for oil and gas suppliers.[22,23]

In the US, recent measurement campaigns have seen broad deployment of new technologies and highlighted the importance of accurately estimating the frequency and duration of intermittent emission events.[24−26] Multiscale measurements of methane emissions at upstream facilities have enabled emissions characterization across a wide range of spatial and temporal scales.[24,26−29] While a disproportionate number of field campaigns have estimated emissions from the upstream production segment, recent measurements have also focused on midstream facilities. These midstream campaigns have been used to update state and national emissions inventories and identify challenges in measuring emissions from complex facilities.[30−35]

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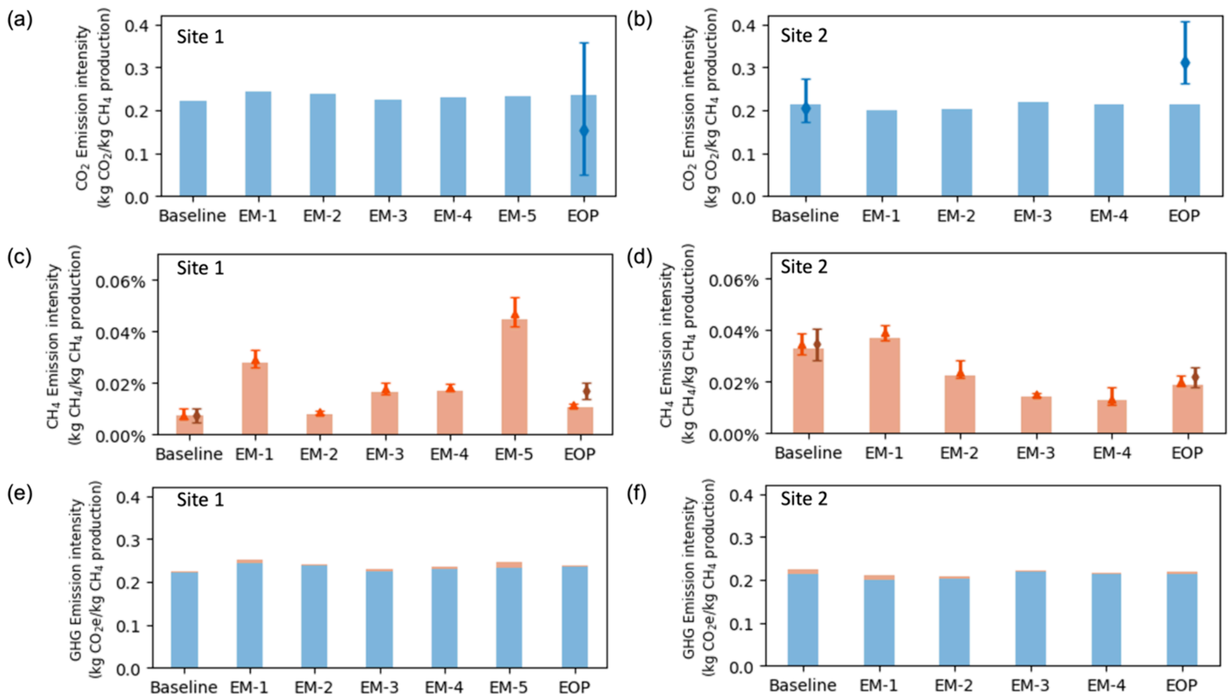

Figure 1. Carbon dioxide and methane emission intensities normalized to natural gas production across two liquefaction terminals. (a, b) CO_2 EI at site 1 and site 2 across baseline, EM, and EOP phases. The CO_2 EI are obtained from OEI (blue bars) and ChampionX measurements (blue diamonds). The ChampionX estimated CO_2 emissions at site 1 baseline is removed because it did not pass quality checks. (c, d) CH_4 EI (orange bars) across all baseline, EM, and EOP phases from Bridger as-measured CH_4 emissions supplemented with turbine exhaust, thermal oxidizer, and OGI-detected fugitive emissions. The median and 95% bootstrapped confidence interval of Bridger measured methane emission intensity after incorporating Bridger's quantification error (orange triangle) are shown across all measurements. The CH_4 EI with uncertainty range obtained from ChampionX measurements are represented by a brown diamond. (e, f) The GHG emission intensity (GWP-100) at site 1 and site 2 calculated based on CO_2 emissions from OEI and Bridger as-measured CH_4 emission (see SI section S8 for GWP-20 estimates and SI section S9 for LNG production normalized EI).

Despite significant expansion in direct methane emissions measurements across the LNG supply chain, no direct measurements at US liquefaction terminals are publicly available, representing a key gap in developing measurement-informed LNG supply chain emissions inventories. Measurements at liquefaction terminals differs from those at other segments of the supply chain due to the larger size and multilevel structures of the facility, which complicate ground-based measurements because many emission sources are inaccessible.[36] Outside the US, there was one recent ground-based measurement campaign at liquefaction terminals.[37] This study deployed a differential absorption LIDAR instrument from a mobile platform, limiting its ability to quantify emissions from inaccessible locations.

In this study, we present results from the first, multiscale periodic surveys of GHG emissions at Sabine Pass and Corpus Christi liquefaction terminals over 16 months. By tracking methane emissions from each source, we demonstrate the role of high-resolution aerial surveys in forming follow-up maintenance activities to reduce methane emissions. By presenting measurement informed GHG emissions intensities at US LNG terminals, this work enables the development of a measurement informed GHG emissions intensity of US LNG supply chains.

2. METHODS AND MATERIALS

2.1. Field Measurements. Multiscale methane emission measurements were conducted at the Sabine Pass and Corpus Christi liquefaction terminals in Louisiana and Texas, respectively, which together accounted for 51% of US LNG exports in 2023.

The liquefaction terminal measurements followed recent protocols established at production and midstream facilities and was divided into three phases: baseline phase to develop an initial snapshot estimate of whole-site CH_4 and CO_2 emissions, an enhanced monitoring (EM) phase that involved a series of periodic measurements over 6−10 months at each liquefaction facility, and an end-of-project (EOP) verification phase.[24,25,30,31]

Three technologies were used to detect and quantify methane and carbon dioxide emissions at the liquefaction terminals, including an aerial LIDAR plume identification system by Bridger Photonics (Bridger), an aerial mass-balance measurement using cavity ring-down spectroscopy by ChampionX (ChampionX), and a ground-based Optical Gas Imaging (OGI) camera survey (SI section S1). The detailed measurement campaign can be found in SI section S2.

2.2. Emissions Inventory Estimates. Two types of bottom-up emission inventories were estimated for each facility. First, the operator calculated the emissions inventory for each site for the duration of each measurement (called the 'operator-estimated inventory' or OEI)—these included both CH_4 and CO_2 emissions, data from stack tests, ground-based LDAR records, flow rates, and other information necessary to calculate a whole-site emissions inventory (SI section S1). Second, the operator also provided the prior year emissions inventory as submitted to the US EPA through the greenhouse gas reporting program (GHGRP).[38]

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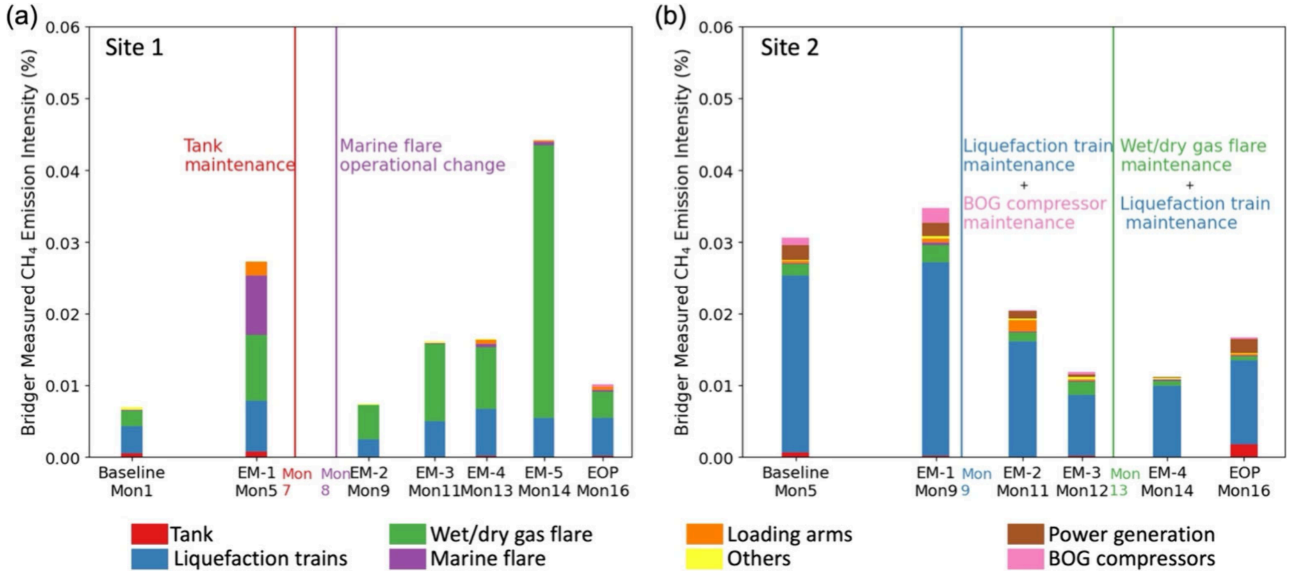

Figure 2. Site-level methane EI across all measurements for two liquefaction terminals ("mon" refers to month), disaggregated by seven major facility groups: tank, liquefaction trains, wet/dry gas flare, marine flare, loading arms, power generation, and BOG compressors. The vertical lines represent different kinds of maintenance operations conducted across these two sites. The specific type of emission reduction is observed after each maintenance.

The measurement informed inventory (MII) is calculated based on whole-site emissions estimates incorporating aerial survey data. Time-averaged MII for CH_4 represents the average of MII at each survey through baseline, enhanced monitoring, and EOP phases. Time averaged MII for CO_2 represents the average of MII at baseline and EOP phases, as the EM phase did not include CO_2 measurements. In this work, the MII for methane is based on Bridger's measurements while the MII for CO_2 was based on ChampionX measurements. Results are reported as methane emission intensity (EI), CO_2 EI, and GHG EI using both 20- and 100-year global warming potential values (SI section S3).

2.3. Quantification Uncertainty. In our study, we propose a new method to estimate the uncertainty in MII that accounts for the skewed estimation error distribution of Bridger's quantification using a quantile regression analysis (SI section S5). The quantile regression analysis provides a conditional distribution of estimation error as a function of the Bridger-estimated emission rate. Nested Monte Carlo (MC) simulations over each pass and source provide uncertainty around whole site MII.

3. RESULTS

In our study, each survey is considered an independent snapshot estimate of emissions, and the emission variation across different surveys is investigated for each facility. We first describe the site-level GHG EI based on the 16-month, multiscale measurement campaign. We then analyze the methane emission variation observed at LNG terminals informed by Bridger measurements, including source-level attribution. We conclude with a discussion of the implication of these data on the development of a global, measurement-informed LNG supply chain EI. Additional analysis regarding the distribution of temporally averaged emissions can be found in another publication.[39]

3.1. Site-Level GHG Emission Intensity. Figure 1 shows the CO_2, CH_4, and total GHG (CO_2e) EI across the two liquefaction terminals for the baseline, EM, and EOP phases. We make three key observations.

First, the CO_2 EI (Figure 1(a,b)) is consistent across surveys at both site 1 and site 2 with average intensities of 0.232 kg CO_2/kg CH_4 and 0.210 kg CO_2/kg CH_4, respectively. Furthermore, the CO_2 EI between the two sites is comparable. The CO_2 emissions from OEI (blue bars) are also consistent with ChampionX mass-balance CO_2 measurements (blue diamonds) in site 1 EOP and site 2 Baseline because CO_2 emissions are largely from combustion processes and can be accurately estimated using fuel consumption volumes and combustion emissions factors. The higher measured CO_2 EI versus OEI estimates in site 2 EOP is likely influenced by unfavorable weather conditions during measurements. Specifically, a low cloud base prevented the airplane from flying over the top of the plume, requiring the use of extrapolation to infer the vertical profile.

Second, methane EI varies over 6-fold across surveys ranging from 0.007% to 0.045%. The methane EIs at EM-1 and EM-5 in site 1 are higher than in other surveys, and we observe a decreasing trend in methane emission intensity at site 2. The ChampionX mass-balance CH_4 measurements (Figure 1(c, d)) are higher than Bridger as-measured methane emissions and is likely an overestimation. The high density of the oil and gas infrastructure around the liquefaction terminals prevented ChampionX from obtaining a clean methane emissions signal associated only with the liquefaction terminals. For example, limitations in the flight path led to the inclusion of sources such as compressor stations, tankers, and wetlands and other non-LNG terminal sources of methane emissions, resulting in a higher estimate compared to Bridger measurements.

Third, the whole-site GHG emissions intensity (Figure 1(e, f)) remains consistent across measurements, as total GHG emission is dominated by CO_2 emissions at liquefaction terminals. CO_2 emission accounts for over 95% of total GHG emission (GWP-100 basis) in each measurement for both sites; thus, variation in methane emissions do not significantly affect the whole-site GHG EI.

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Because of the skewed error distribution associated with Bridger's quantification as identified in recent controlled release tests,[40] the uncertainty range in the methane EI (Figure 1(c, d)) does not follow a normal distribution. This results in an asymmetric confidence interval around the median methane EI, suggesting a small non-zero bias in quantification estimates (SI section S5).

3.2. Role of Maintenance Activities in Reducing Methane Emissions. Figure 2 shows the site-level methane EI across all surveys for the two terminals disaggregated by major source categories. The data for each survey are spaced along the *x*-axis based on the time of measurement. The vertical lines represent various maintenance activities undertaken over the same time period. We observe significant reduction in methane emission from each source after corresponding maintenance activities at both sites. The liquefaction train emissions exhibit a decreasing trend after maintenance, with the lowest liquefaction train emissions in EM-3 being 69% lower than those in EM-1. We further find that seal gas valve emissions in liquefaction trains in site 2 is reduced from 0.018% kg CH_4/kg CH_4 production during EM-1 to 0.002−0.005% kg CH_4/kg CH_4 production in the subsequent surveys after maintenance. The fugitive valve emissions in BOG compressors identified during EM-1 are no longer visible in subsequent surveys after maintenance. Therefore, we conclude that high-resolution aerial surveys can enable timely maintenance for emissions mitigation, especially when aerially detected sources are typically not surveyed by the OGI due to inaccessibility. More discussion about the role of maintenance activities could be found in SI section S12.

We also observe significant methane EI variations at both the site-level and source-level across surveys at both facilities. At site 1, the methane EI ranges from over 0.04% to below 0.01%. At site 2, the site-level EI shows a decreasing trend over the 16-month campaign, which can be attributed to decreasing liquefaction train emissions after maintenance activities.

The large site-level emission variation in site 1 is caused by significant variation in flare-related emissions. However, we recommend caution in interpreting flare-related, aerial measurements at liquefaction terminals as the effectiveness of aerial quantification of flare emissions at liquefaction terminals is an open research question (see SI section S7).

3.3. Value of OGI Follow-up Survey. Figure 3 shows a reconciliation between the ground based OGI follow-up survey and the aerial Bridger survey. There are four possible scenarios: (1) *OGI identified:* the location of the Bridger-identified emission source is confirmed by the OGI crew; (2) *OGI not found:* the OGI crew did not find any emissions associated with a Bridger-identified emission source; (3) *OGI inaccessible:* the OGI team cannot access a Bridger detected emission source because of safety or logistical considerations; (4) *No OGI follow up:* no OGI follow-up was initiated due to either known limitations of OGI or OGI follow-up would not provide new information for that source. All EI contributions shown in Figure 3 are based on Bridger measurements since the OGI crews did not quantify emissions for all detected sources.

First, OGI cannot be used to estimate whole-site emissions at liquefaction terminals because the OGI cameras cannot reach all potential emission sources at these facilities. At site 1, more than 58% of the Bridger-identified emissions across the whole site were not accessible by the OGI crew. At site 2, the percentage of inaccessible emissions of the OGI is around 9−15%, lower than that in site 1. The different percentages of inaccessible OGI emissions between sites 1 and 2 are associated with different categories of dominant emissions in these two sites.

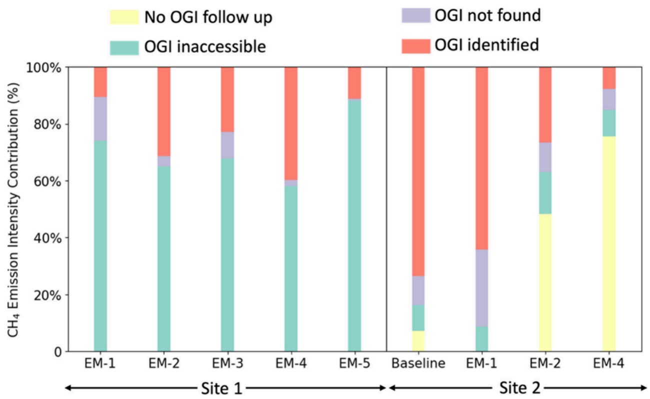

Figure 3. Emission reconciliation between ground based OGI follow-up survey and aerial Bridger survey. Confirming Bridger detections using OGI follow-up presents three options: (1) OGI identified possible sources (orange), (2) OGI did not find emissions found by Bridger (purple), (3) OGI could not access the source (green). Emissions found by Bridger that were not followed up by OGI are shown in yellow. The *y*-axis represents the methane emission intensity contribution of each scenario of OGI/Bridger detection.

Second, OGI is unable to detect all emission sources at a facility compared to aerial survey, an issue that has also been demonstrated across other supply chain segments.[41] In this study, when considering only those sources that the OGI attempted to find, up to 50% or more of emissions identified by Bridger were not found by the OGI at both sites.

Table 1 shows the comparison of CH_4, CO_2, and total GHG emission intensity between GHGRP and MII estimates at both sites. First, the 2022 GHGRP reported methane emission intensity is 74−88% lower than time-averaged MII methane estimates for both sites. This observation demonstrates the underestimation of methane emissions in activity-based inventories, which is consistent with recent measurement studies across upstream and midstream segments of LNG supply chains. We also find that time-averaged MII relying solely on Bridger measurement is similar to time-averaged MII relying both on Bridger and ChampionX measurements, which indicates the consistency of methane emission estimates between Bridger and ChampionX measurements. In addition, we find that the GHGRP reported CO_2 emissions is consistent with time averaged MII CO_2 emission estimates for both sites. More importantly, since CO_2 emissions contribute to more than 95% of total GHG emissions (GWP-100 basis) for both sites, the GHGRP 2022 reported total GHG reasonably matches time-averaged MII estimated GHG emissions to within measurement uncertainty. CO_2 EI at site 1 is based on the OEI as measurements by ChampionX did not pass quality checks during analysis. Measured CO_2 EI at site 2 is also consistent with remote sensing derived EIs at liquefaction terminals.[42]

The range of methane EIs measured in this study are comparable to estimates from a recent empirical measurement campaign.[37] Comparisons with other nonempirical estimates of methane EI at liquefaction terminals are discussed in SI (SI section S10).

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Table 1. Comparison of CH_4, CO_2, and Total GHG Emission Intensity (GWP-100 basis) between GHGRP 2022 Reporting and MII Estimates at Both Sites[a]

Site	GHG type	GHGRP2022	Time-averaged MII (Bridger + Champion X)	Time-averaged MII (only Bridger based)
Site 1	CH_4 (%)	0.005	0.019 (0.018−0.023)	0.019 (0.018−0.022)
	CO_2 (kg CO_2/kg CH_4 production)	0.217	0.232[b]	/
	CO_2e (kg CO_2e/kg CH_4 production)	**0.218**	**0.238**	/
Site 2	CH_4 (%)	0.003	0.024 (0.022−0.028)	0.023 (0.022−0.028)
	CO_2 (kg CO_2/kg CH_4 production)	0.227	0.258 (0.218−0.299)	/
	CO_2e (kg CO_2e/kg CH_4 production)	**0.228**	**0.265**(0.225−0.307)	/

[a]The values in the parentheses represent 95% confidence interval. [b]OEI used for CO_2 emissions estimates at site 1 as direct measurements during baseline was rejected during QA/QC.

Variability in the methane EI at liquefaction terminals is a key feature of our measurement campaign. Furthermore, the complex three-dimensional nature of a liquefaction terminal where each liquefaction train could have over five levels makes ground based LDAR surveys time-consuming and ineffective. Safety and logistical considerations prevent ground crews from accessing several parts of the facility. Thus, aerial surveys that have been demonstrated to effectively estimate all emission sources above their detection threshold followed by ground based OGI to identify emitting components and initiate follow-up action can be an effective LDAR program. Even with aerial surveys, the complex nature of a liquefaction terminal will affect plume development. For example, a persistent fugitive emission source on the lower levels of a liquefaction train could appear intermittent on an aerial survey if the plume rise is blocked by higher levels of the train. Thus, interpretation of aerial survey data requires an understanding of the underlying processes and operational information that can indicate the temporal nature of a source. In this work, we took the conservative option to assume all sources are persistent; future work should focus on evaluating intermittency at these facilities.

This work provides the first measurement informed GHG EI estimates at US liquefaction terminals by employing multiscale measurement technologies. In addition, we demonstrate the role of aerial directed measurements in potentially informing operational maintenance for methane emission mitigation. Finally, we conclusively demonstrate that reported GHG EI of the liquefaction terminals in our study reasonably matches measurement-informed GHG EI. This conclusion differs from every other segment of the natural gas supply chain, where MIIs are higher than reported inventory estimates. This is because carbon dioxide emissions, which can be accurately estimated using fuel emissions factors, comprise more than 95% of all GHG emissions. Thus, in the context of developing LNG supply chain emission intensity, the use of GHGRP-reported EI provides reasonably accurate estimates of total GHG emissions at liquefaction terminals. While our measurements were conducted at two Cheniere-operated liquefaction terminals, which represent approximately half of the total U.S. LNG exports in 2023, emissions intensity may vary across other existing liquefaction terminals. This variability is unlikely to change our conclusion since CO_2 emissions are stoichiometric and dominate total GHG emissions at US LNG terminals.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.estlett.4c00713.

Additional information referenced in the manuscript related to measurement technologies, measurement campaign, methane emissions intensity, Bridger measurement data analysis methodology, Bridger quantification uncertainty analysis, reconciliation between two aerial measurements and OEI, reconciliation between OEI and MII, flare measurements, GHG emission intensities under 20-year global warming potential, and GHG emission intensities normalized to LNG production, and comparison of methane EIs to other published studies (PDF)

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Author Contributions

F.C.G. conceived the study. A.P.R., G.R., S.A.R.W., and F.C.G. designed the measurement campaign. Y.Z. analyzed the field data, developed new models for measurement-informed inventories and uncertainty estimates, and wrote the paper. All authors contributed to the discussion and interpretation of results and reviewing the paper.

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Notes

The authors declare the following competing financial interest(s): F.G. and G.R. are currently employees of Cheniere Energy Inc. S.A.R.W was an employee of Cheniere till May 2024, and is currently an employee of SLR International. SLR International performs work for Cheniere, other oil and gas industry clients, academic institutions, and industry research organizations. A.P.R. is currently a member of the Gas Pipeline Advisory Committee of the US Department of Transportation; in this role, he is a Special Government Employee. A.P.R. has current research support from the US Department of Energy, Environmental Defense Fund, and sponsors of the Energy Emissions Modeling and Data Lab (EEMDL).

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