Emissions dissonance: Examining how firm-level under-reporting undermines policy

Marc Lepere[1], Simone Maso[2], Yao Dong[2], David Aikman[2]

[1] *King's Business School, King's College London*

[2] *Qatar Centre for Banking & Finance, King's Business School*

WORKING PAPER[1]

This draft: May 2025

Abstract

This study examines the phenomenon of under-reporting GHG emissions (scope 1) at firm-level by exposing significant gaps, or dissonance, between emissions from company facilities that have been observed from satellite data (observed emissions) with emissions reported in company filings and public disclosures (reported emissions). We find total observed emissions are more than three times reported emissions for under-reporting companies in our dataset. Emissions dissonance is widespread in the energy sector. If a company operates in the energy sector, it is 21.92% more likely that it will under-report its emissions. Under-reporting by oil and gas companies can spillover via emissions on company value chains to impact the wider economy. We conclude that while company reporting may be a necessary basis for policy, it is unlikely ever to be sufficient. For under-reporting energy companies, we find a relatively weak regulatory framework, fragile market pricing incentives, low incidence of litigation risk and tenuous reputational risk. We recommend the default use by policymakers of advanced measurement data from satellite and remote sensing technologies to automatically observe annual methane emissions from oil and gas facilities, and to make these default emissions (DefCH_4) the *de facto* standard for oil and gas companies.

Keywords: GHG Emissions, Corporate Reporting, Materiality, Environmental Risk, Financial Risk, Energy.

---

[1] The authors would like to thank Yael Lifshitz (Dickson Poon School of Law, King's College London), Luca Taschini (University of Edinburgh) and Corey Walrod (IFRS, ISSB Technical Staff) for helpful discussions and feedback on this draft. All errors are our own.

Introduction

Financial regulators worldwide including the European Securities and Markets Authority, the China Securities Regulatory Commission and the U.S. States of California, New York, Colorado, New Jersey and Illinois are joining with the International Organisation of Securities Commissions and International Financial Reporting Standards Foundation in requiring companies to disclose their greenhouse gas (GHG) emissions. By establishing consistent and comparable emissions disclosures, regulators hope to incentivise firms to improve their understanding of their carbon footprints, while also enabling financial markets to price this information, incentivising decarbonisation efforts.

Moreover, policymakers are making company reporting of GHG emissions a necessary condition for decarbonisation regulation and/or market-based incentives (Ilhan et al., 2023). For example, the European Union's Carbon Border Adjustment Mechanism (effective January 2026) requires importers of carbon-intensive products to declare embedded emissions and purchase certificates to an equivalent value based on the EU carbon market. The aim is to achieve a level carbon-emissions playing field between imported and domestically produced carbon-intensive products (European Commission, 2024). Without accurate emissions data, market-based systems such as CBAM would not function effectively (European Commission, 2020).

To enable compliance regulators are considering how best to combine advanced measurement data from satellite and remote sensing technologies (sometimes called "top-down" methods), with 'bottom-up' methods of emissions reporting deployed by companies. The California Air Resources Board announced (21 March 2025) a project to purchase GHG emissions data collected by commercially operated satellites from sites around the State, such as oil and gas operations, landfills and livestock facilities. The aim is to gather information on GHG emissions that may otherwise go unreported and is "much closer to real time than the data now available" (California Air Resources Board, 2025)[2].

In this paper, we provide fresh evidence on the scale of inaccuracies in reported GHG emissions to suggest that while reporting by companies may be necessary, it is unlikely ever to be a sufficient basis for policy. We do so using a simple method that compares firms' reported emissions with new publicly available information on emissions observed from satellite imagery.

---

[2] The $100 million project is funded by California's cap-and-trade program that requires power plants, natural gas providers and large industries that emit greenhouse gases to buy permits for the emissions they produce (California Air Resources Board, 2025).

Our satellite data are from *Climate Trace*, an independent not-for-profit GHG-tracking dataset, which integrates data from over 300 satellites and thousands of land-, air-, and sea-based sensors to provide observations on the scope 1 GHG emissions of millions of company installations globally. We aggregate the information in this dataset into firm-level emissions using a text-based matching algorithm and compare these estimates with company-specific reported emissions from the *Refinitiv Eikon* dataset. Altogether we obtain an accurate match for 279 distinct companies worldwide, a sample that reflects activities in a range of sectors and countries.

We report two key findings. First, we find that over a quarter of the companies in our matched dataset (75 of 279) are currently under-reporting their scope 1 emissions, i.e., their reported emissions from *Refinitiv Eikon* are at least 20% lower than their observed emissions in *Climate Trace*. The difference between observed and reported emissions for these companies is highly significant both statistically and environmentally: the median level of under-reporting is 248% of reported emissions, with the inter-quartile range spanning 121%-699%. Aggregating across the firms in our sample, we find that their overall emissions are likely to be 0.33 Gigatonnes (Gt) of CO2e higher than previously thought, a 242% increase. Concerningly, thirty-five of the under-reporting companies in our sample disclose that their CSR/sustainability reporting is audited.

Second, rather than being randomly distributed across countries and sectors, the under-reporting companies in our sample are U.S.-based and located in the energy-sector (specifically, in oil and gas production)[3]. Thirty-three of the 75 under-reporting companies are U.S.-based energy companies – this is 44% of our sample compared to 14% in our full dataset. Of the remainder, 14 are energy companies operating outside the United States, 23 are companies in the utilities and materials sectors, with the remaining five companies operating in the industrial and real estate sectors. The U.S.-based energy companies tend to be mid-scale in terms of market capitalisation and employment and include firms such as Occidental Petroleum, Pioneer Natural Resources and Diamondback Energy. Intriguingly, they also tend to be in states with lax climate-risk disclosure requirements such as Texas and Oklahoma. While our sample is not sufficiently large to make sharp causal statements about the drivers of under-reporting, our results are at least consistent with the notion of weak regulation being an enabling factor. Our

[3] Companies appear in the 'energy' sector in *Refinitiv Eikon* and in 'oil and gas production' sub-sector in *Climate Trace*.

analysis suggests no significant regulatory, financial, litigation or reputational incentives for U.S. oil and gas companies to improve reporting.

What are the implications of our findings? First, and most importantly, if a significant proportion of companies worldwide are materially under-reporting their GHG emissions, then efforts to decarbonise the global economy may be further out of reach than previously thought. As a thought experiment, if the scale of under-reporting we document is representative of the global energy sector, global emissions could be 9.48 Gt CO2e larger than currently understood. This would represent a significant share (3.64%) of the carbon budget that IPCC scientists estimate remains if we are to keep the scale of global warming below 1.5 degrees C relative to pre-industrial levels (Forster et al., 2022).

Second, the United States is the world's largest emitter of methane from oil and gas operations[4] — if U.S. energy companies (again, oil and gas producers) continue to systematically under-report then efforts to reduce methane emissions in the short-term will be retarded. Reducing methane emissions is the "fastest, most cost-effective way to slow the current rate of warming" (UNEP, 2024)[5]. This is because methane is estimated to be 25 times more harmful than carbon dioxide. A rise in atmospheric methane, on a 20-year time scale is estimated to have 80 times the warming power of carbon dioxide (Sobanaa, et al., 2024).

Third, our findings suggest that the GHG Protocol as currently devised is not sufficiently robust to underpin regulators' goals of using mandatory GHG disclosures as a tool to incentivise companies to decarbonise their activities. Regardless of whether under-reporting is deliberate or not, it means that under-reporting companies have a misleading understanding of their carbon footprints. Moreover, customers of under-reporting companies may in turn be unintentionally under-reporting their own scope 1, 2, 3 and total GHG emissions, exposing them to reputational and financial risk. This spillover effect is detrimental to the calculation of firm- and sector-level emissions throughout the economy and undermines policy.

We conclude by recommending the default use by policymakers of advanced measurement data from satellite and remote sensing technologies to automatically observe annual methane emissions from oil and gas facilities, and to make these default emissions

[4] Measured by methane intensity. Methane emissions intensity is a measure of the methane component of natural gas emissions relative to the methane component of natural gas produced.
[5] CH_4 emitted from human activity is estimated to be responsible for around 35% of the global warming that has already taken place (UNEP, 2024).

($DefCH_4$) the *de facto* standard for oil and gas companies worldwide, with the option for reporters to adjust $DefCH_4$ using approved methods for year-end reconciliation ($AdjCH_4$).

Related Literature and Contribution

Our findings relate to various strands of the existing literature on emissions measurement and disclosure. While there is a common understanding that firms' scope 3 emissions are poorly measured and subject to significant biases (Fouret et al., 2024), we are amongst the first to document significant issues with scope 1 information. We deploy data from satellite and remote sensing technologies, which we term 'observed' emissions with GHG inventories disclosed in company reports, termed 'reported' emissions.

Reported emissions require the preparation of GHG inventory, which as a process is fundamentally uncertain. Researchers have examined the scientific and estimation uncertainties of GHG emissions (Cenci & Biffis, 2025; Winiwarter and Rypdal, 2001; Monni, Syri and Savolainen, 2004; Monni et al., 2007; Bun et al., 2010; Venkatesh et al., 2011; Lee et al., 2020). GHG emissions can be gamed due to the existence of approved multiple calculation methods and emission factor databases, leading to significantly different emissions estimates for same activity data inputs (Aikman et al., 2023).

The calculation of observed emissions can also be uncertain, depending on the satellite and aerial technologies deployed (Conrad et al., 2023). Continuous monitoring systems can provide valuable data for determining the duration of emission events, and do so more quickly than survey methods, but typically have high uncertainty in quantifying total emissions (Bell at al., 2023). Not withstanding uncertainty, in 2022 the IPCC suggested that atmospheric measurements could serve as an ideal tool for testing and validating reported emission inventories, especially given recent scientific advancements and the independence of this data[6].

Recent studies are increasingly relying on satellite data and atmospheric measurements combined with inverse modelling to trace GHG emissions back to their most probable sources (Fung et al., 2023; Flerlage, Velders, & Boer, 2021; Vaughn et al., 2018). Using satellite and continuous monitoring methods several studies have found significant discrepancies between inversion estimates and national inventories (Deng et al., 2023), as well as gaps between observed emissions and reported methane emissions in the U.S. oil and gas sector (Sherwin et al., 2024; Alvarez et al., 2018). At the firm level, Fan, Thomas, & Zhang (2024) used satellite data to

[6] https://www.ipcc-nggip.iges.or.jp/public/mtdocs/pdfiles/2209_AtmObs_Report.pdf

compare firms' actual carbon emissions with their reporting data, finding that over 60% of the sampled firms under-reported their emissions.

Financial disincentives can provide a motive for companies to either reduce or under-report emissions. Firms with higher emissions face a higher cost of equity (Bolton & Kacperczyk, 2021, 2023) and increased loan spreads (Kleimeier & Viehs, 2018), which have become even more significant after the Paris Agreement (Ehlers et al., 2022). Furthermore, high-emission companies receive less bank credit (Kacperczyk and Peydró, 2022) and experience penalties from customers (Fan, Thomas, & Zhang, 2024).

Our study contributes by identifying the dissonance between observed and reported total scope 1 GHG emissions at firm-level; and analysing the lack of incentives, environmental materiality and spillover risk associated with under-reporting. Our findings complement existing studies by: (i) aggregating emissions reporting to firm-level rather than at facility level; (ii) reporting at firm-level compared to regional, industry or sector level; (iii) studying GHG emissions expressed as carbon dioxide equivalent (CO2e) emissions compared to studies focused on individual GHGs like methane (CH_4) or nitrous oxide (N_2O); (iv) extending the analysis to include the direct spillover effects of under-reporting scope 1 emissions on oil and gas firms' value chains via customers' GHG emissions; and (v) recommending the default use of advanced measurement data from satellite and remote sensing technologies to automatically observe annual methane emissions from oil and gas facilities in a policy we term 'default emissions'.

The remainder of this paper proceeds as follows: a detailed description of data sources and methodology (Section 2); results and analysis of possible explanations for under-reporting in the U.S. energy sector (Section 3); an examination of the material environmental and spillover risks of under-reporting (Section 4); and conclusion and policy recommendation (Section 5). The Annex contains a probit regression to explore the relationship between firm characteristics and likelihood of under-reporting emissions (Annex 1); a review of the state-of-the-art of observed emissions (Annex 2); a table of observed and reported emissions for each under-reporting company (Annex 3); the International Energy Agency's marginal abatement cost curve for methane (Annex 4); and the U.S. Environmental Protection Agency's estimated incremental labour costs of improved GHG reporting (Annex 5). The terms 'GHG' and 'CO2e' are used interchangeably throughout.

2. Data and methodology

To capture observed emissions, we use the *Climate Trace* dataset, a global emission tracking initiative that integrates data from over 300 satellites and thousands of land-, air-, and sea-based sensors to provide near-real-time information on GHG emissions at the installation level. The dataset, which is publicly available, includes emissions data from 10 sectors and approximately 80 subsectors, and includes information on various gases, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (NO_2). Unlike the only other programme offering firm-level data *GHGSat*, which is a commercial satellite-based programme targeting individual facilities on demand, *Climate Trace* is free to access and is a not-for-profit collaboration of over 100 non-profits, tech companies, universities, researchers, and climate experts. We are concerned with the accuracy of firm-level GHG emissions.

Climate Trace does not publicly disclose specific numerical margins of error for its emissions estimates from oil and gas facilities. It is however transparent in its methodologies which use a hybrid approach to estimate atmospherically observed emissions, combining a variety of peer-reviewed models bespoke to the oil and gas industry.[7] One such model provides site-level analysis of production emissions, methane venting, fugitives, flaring, super-emitter events (e.g., gas leaks), on-site fuel consumption, biogenic emissions caused by changes to the ecosystem around the facility, embedded emissions (e.g., cement casings) and electricity consumed (Brandt et al., 2021). Another covers fugitive and exhaust emissions from crude oil refinery using an assay library of over 600 crude oils worldwide. The library contains specific information on the chemical properties of each type of crude, essential to accurate estimation of GHG emissions (Jing et al., 2020).

Data from *Climate Trace* is consistent with findings that methane emissions are under-reported compared to results from satellite and aerial technologies (Deng et al., 2022). There is consensus that the scale of observed emissions is between two times higher than reported for oil & gas companies in Australia[8] (Knight, A.-L. et al., 2025) and Canada (Chan, et al., 2020), and roughly three times across 6 regions of the United States (Sherwin, et al., 2024). *Climate Trace* is selected from several leading satellite databases/programmes (detailed in Appendix Table A2.).

---

[7] In 2022 data the Oil Climate Index + Gas (OCI+) model is combined with the Oil Production Greenhouse Gas Emissions Estimator (OPGEE) and the Petroleum Refinery Life-Cycle Inventory Model (PRELIM). OPGEE was developed by the California Air Resources Board and Stanford University (Brandt et al., 2021); PRELIM by the University of Calgary (Jing et al., 2020).

[8] The report also estimated emissions could be three times higher for open-cut coal miners.

Each facility is identified by country, state, sector (e.g., manufacturing), subsector (e.g., cement), company, longitude and latitude and the proportion of the facility operated by the company. Additionally, four levels of data are available: (i) monthly CO2-equivalents (CO2e) in metric tonnes over 20 or 100 years, for any year between 2021-2025 (with a 2-month lag); (ii) other emissions i.e. individual GHGs CO_2, CH_4 and NO_2 and non-GHG air emissions (e.g., ammonia, sulphur dioxide, particulate matter); (iii) confidence level (a five point-scale from very low to very high) in emissions, capacity/size of the facility and total emitting activity; and (iv) metadata includes a unique asset ID, asset type (e.g., a cement plant) and name of the data lead i.e. the organisation providing the data. The data we use from *Climate Trace* were downloaded on 17 March 2024 and cover CO2e emissions in metric tonnes over 100 years for the calendar year 2022.

To calculate observed emissions for a specific company, we search *Climate Trace* for all the installations associated with that company. Since a single installation can be owned by multiple companies, *Climate Trace* provides the percentage of ownership for each installation. For example, the share of interest held in each facility by ARC Resources Limited (a Canadian oil and gas company) in Montney, Alberta is 43.37%; in Montney, British Columbia is 16.85% and in Peace River is 1.43%. Using the operational control method of apportioning GHG emissions (GHG Protocol, 2015), we allocate emissions for each facility proportionally based on the operational share of each company. While *Climate Trace* provides emissions estimates for 395 million emission sources globally covering 80 subsectors, information on the owner or the operator of each installation is only available for 14 of these subsectors, covering 10,192 unique companies.

To obtain data on reported emissions, we use the *Refinitiv Eikon* database, which holds environmental, social, governance (ESG) information for over 9,000 companies, facilitating comparison across companies, industries, and countries. *Refinitiv Eikon* gathers data from publicly available corporate documents such as Annual Reports and regulatory filings (Form 10-K), as well as CSR, Sustainability, and ESG Reports. We selected those companies in *Refinitiv Eikon* that reported CO2e scope 1 emissions for the calendar year 2022[9], resulting in a total of 5,970 companies. We also collected from *Refinitiv Eikon* data on the number of employees, revenues, market capitalisation, headquarter location, GICS sector[10], whether the company's

[9] Available in 2023-2024.
[10] The Global Industry Classification Standard is an industry taxonomy developed by MSCI and S&P for use by the financial community. The GICS structure consists of 11 sectors, 25 industry groups, 74 industries and 163 sub-industries. (https://www.msci.com/our-solutions/indexes/gics)

reported CO2e emissions are audited or not, and whether the company is in private or public ownership.

As *Climate Trace* and *Refinitiv Eikon* do not share a common identifier, we use the De Nederlandsche Bank (DNB) company name matching Python package to match companies across these databases.[11] This tool enables us to merge the two datasets based on company names, using a fuzzy matching algorithm. Each match is given a score from 0 to 100, and we retain only matches with a perfect score of 100. It is important to note that there may be cases where a company in each of *Refinitiv Eikon* and *Climate Trace* have identical spellings but are different companies. To resolve this, we manually verify all installations located in countries different from the company's headquarters. As a result, we obtain a final dataset of 279 companies, for both observed and reported emissions.

3. Results

The focus of our analysis is the gap between observed and reported emissions, which we calculate as $\mathrm{PE}_i = \frac{\mathrm{Emissons}_i^{\mathrm{TRACE}} - \mathrm{Emissions}_i{}^{\mathrm{REF}}}{\mathrm{Emissions}_i{}^{\mathrm{TRACE}}}$, where PE_i is the percentage error for company *i*, $\mathrm{Emissions}^{\mathrm{TRACE}}$ are the observed emissions from *Climate Trace* for company *i*, and $\mathrm{Emissions}^{\mathrm{REF}}$ are the reported emissions from *Refinitiv Eikon* for company *i*.

We classify the 279 companies in our matched dataset into three groups based on their PE, using a threshold of ±20%. This threshold is aligned with Solazzo et al., (2020) who find that the anthropogenic emissions estimated by Emission Database for Global Atmospheric Research (EDGAR) are within an accuracy range of -15% to +20%. Our threshold of ±20% acknowledges the scientific, methodological and parametric uncertainties inherent in both reported GHG emissions (IPCC, 2022) and in observed estimates using satellite and aerial technologies (Conrad et al., 2023) and continuous monitoring systems (Bell at al., 2023).

Group 1 comprises those companies whose PE is within this threshold, i.e., where the difference between reported and observed emissions lie within ±20% of observed emissions; Group 2 are companies whose PE is lower than −20%, indicating that their reported emissions are 20% or more above their observed emissions; and Group 3 are companies whose PE is greater than +20%, indicating that their reported emissions are 20% or more below their observed. A priori, we might expect there to be a bias towards classification in Group 2, as not

[11] https://medium.com/dnb-data-science-hub/company-name-matching-6a6330710334

all the operations of a large company will necessarily be captured within the *Climate Trace* database.

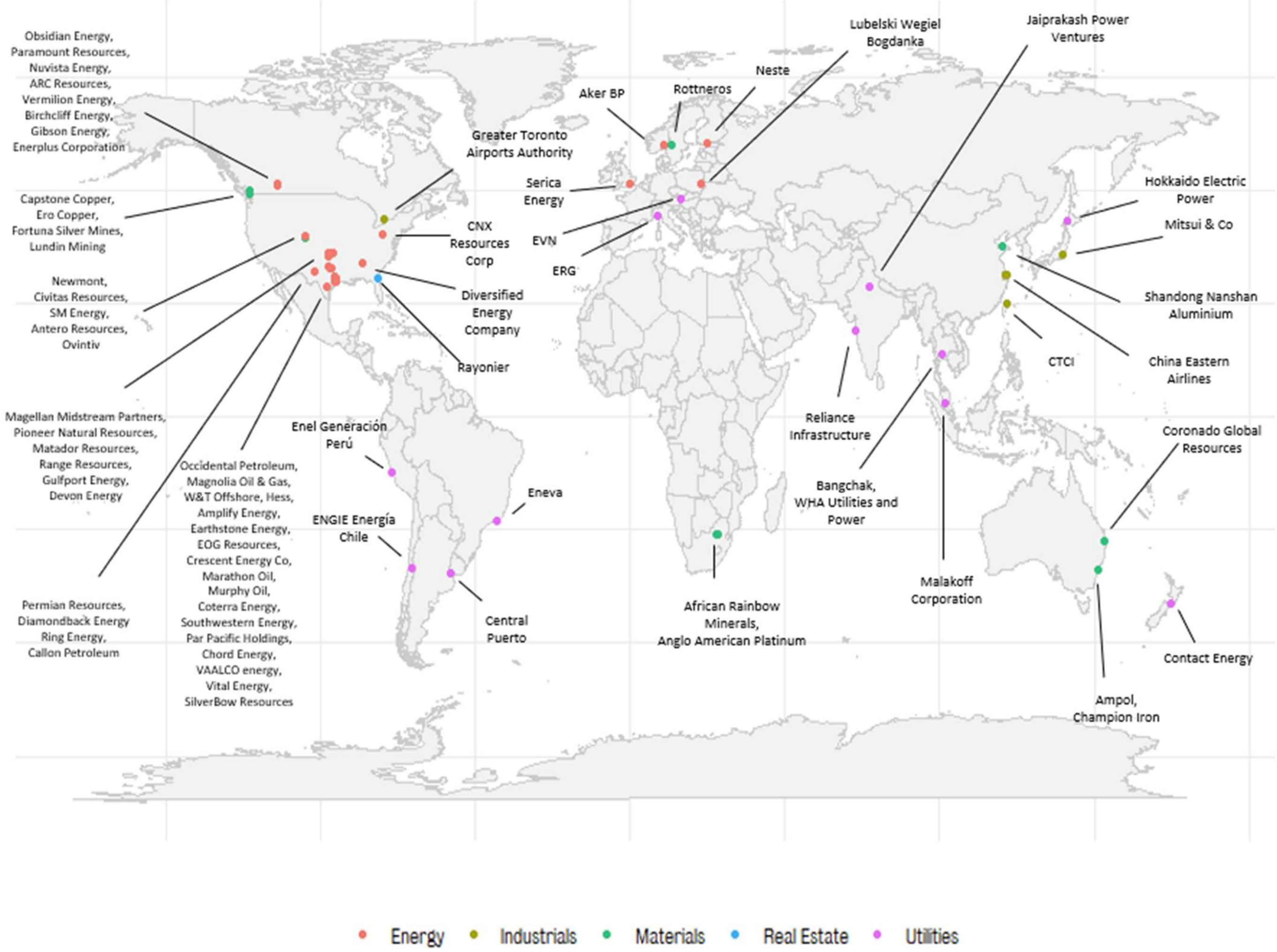
Table 1 presents the results of this classification. We find that 90% of the companies in our sample have significant discrepancies between their reported and observed emissions. The majority of these (175 companies) are in Group 2, indicating that their reported emissions in *Refinitiv Eikon* significantly exceed those we can account for in *Climate Trace*. This is unsurprising for the reason given above. More surprisingly, however, we find that 75 companies (27% of the sample) lie in Group 3, indicating that their reported emissions are at least 20% below those we can account for in *Climate Trace*. This must reflect either misreporting by the companies themselves or errors in either *Refinitiv Eikon* or *Climate Trace*. Henceforth, we refer to these firms as under-reporting companies.

Table 1. Comparison of observed and reported emissions.

Groups		**Number of Companies (n)**	**Percent over total**
1	Refinitiv ≈ Trace	29	10%
2	Refinitiv > Trace	175	63%
3	Trace > Refinitiv	75	27%
	Full sample	**279**	**100%**

Figure 1. lists the under-reporting companies by name and sector and maps the location of their headquarters. Evidently, these companies are headquartered primarily in the U.S. and Canada, with some observations in Europe, Latin America and Asia. They operate in the energy, industrials, real estate and materials sectors (as defined by GICS). Overwhelmingly under-reporting companies in group 3 are quoted on public stock markets (92%).

Figure 1. Location of under-reporting companies by location of headquarters



In Tables 2-4, we report further characteristics of the 75 under-reporting companies – our objective is to understand whether companies in group 3 are distinct from those in the total matched sample. Table 2 demonstrates that under-reporting companies are disproportionately found in the energy sector[12], relative to the full sample.

---

[12] In the GICS sector classification, the energy sector includes all stages of the oil and gas industry – ranging from drilling and production to marketing, transportation and associated services.

Table 2. Characteristics of under-reporting companies by sector

	Energy	Utilities	Materials	Other	Total
Group 3 (n = 75)	47 (63%)	12 (16%)	11 (15%)	5 (6%)	75 (100%)
Full sample (n = 279)	79 (28%)	68 (24%)	90 (32%)	42 (16%)	279 (100%)

Note: According to GICS sector classification 'Other' category includes communication services, consumer discretionary, consumer staples, financials, health care, industrials, IT and real estate.

Table 3 shows that under-reporting companies also tend to be generally smaller (albeit by no means small) in terms of revenue, market capitalization, and number of employees.

Table 3. Characteristics of under-reporting companies by size

	Full sample (n = 279)				Group 3 (n = 75)			
	Obs.	Mean	Median	St. Dev	Obs.	Mean	Median	St. Dev
Revenues (billion USD)	276	19.60	6.39	47.94	74	6.94	3.04	13.68
Market cap. (billion USD)	272	29.40	4.93	191.35	74	9.33	3.15	15.27
Employee (thousand)	255	22.679	6.20	54.46	68	4.108	0.976	11.35

Table 4 shows that under-reporting companies are significantly more common in North America than the geographical split in the full sample would imply.

Table 4. Characteristics of under-reporting companies by location of headquarters

	Asia	Europe	North America	Other	Total
Group 3 (n = 75)	10 (13%)	7 (9%)	48 (64%)	10 (14%)	75 (100%)
Full sample (n = 279)	99 (36%)	55 (20%)	98 (35%)	24 (9%)	279 (100%)

Within North America, we observe that 47% of companies in Group 3 (n = 33) are based in the United States, compared to only 23% in the full matched sample (n = 64); somewhat less strikingly, 17% of companies in Group 3 (n = 13) are Canadian, compared to 12% in the full matched sample (n = 34). Finally, we note that Group 3 companies are less frequently audited for Corporate Social Responsibility matters than are firms in the full sample: the percentage of companies audited for CSR is 46% in Group 3, compared to 63% in the full sample.

We next explore the relationship between firm characteristics and likelihood of under-reporting emissions via a Probit regression in which the dependent variable is a binary indicator that equals one if a firm under-reports its emissions. Based on the descriptive analysis above, we include as controls whether the company operates in the energy sector, is headquartered in the U.S. or Canada, and whether it is audited for CSR; we also control for company size (measured by log revenue) and for reported (log) emissions from *Refinitiv*.

Table 5. presents the marginal effects from this regression. Column 1 shows the impact of each regressor individually, whereas column 2 includes an interaction term between the energy sector and firms headquartered in the U.S. (see Annex 1. for regression table). Our findings indicate that individually belonging to the energy sector and being headquartered in the U.S. significantly and positively increases the probability of under-reporting. In contrast, being headquartered in Canada or not being audited for CSR does not influence the misreporting likelihood. Additionally, the controls reveal that higher reported emissions and larger company size are associated with a lower probability of under-reporting, likely due to the stricter scrutiny faced by larger firms[13].

Table 5. Probit regression: marginal effects

	(1)	(2)
Emission	-6.95%***	-6.36%***
Size	-3.15%*	-2.76%*
Energy	21.92%***	16.19%**
US	13.87%***	-5.50%
CA	-2.61%	-0.81%
Not audited	-1.20%	-1.19%
Energy & US		47.94%***

Note *p < 0.10, **p < 0.05, ***p < 0.01.
Missing (log) revenues values are replaced by the (log) of market capitalization.

[13] Results are robust when substituting emissions with emission intensity.

Our key finding, however, relates to the effects of interacting the energy sector control with being headquartered in the United States. This interaction term is highly significant, both statistically and environmentally. To give a sense of the scale of this effect, we calculate the implied marginal impact on the probability of under-reporting. We find that if you knew nothing about a company other than it was headquartered in the U.S. and it operated in the energy sector, then you would increase the probability assigned to this company being in the under-reporting category by 48% points. (This is relative to the unconditional probability of being in Group 3 of 27%.) This is consistent with the fact that of the 35 U.S. companies allocated to Group 3, 33 belong to the energy sector[14].

In seeking to explain these findings, one possible concern is that the energy sector may be disproportionally represented in the *Climate Trace* dataset. This is not the case: *Climate Trace* includes emissions data on 395 million individual emitting facilities, farms, forests, and other assets in 10 sectors and approximately 80 subsectors. The dataset includes 473 individual oil and gas production, and transport sources compared to 8,134 electricity generation sources and 1,266 mineral extraction sources of GHG emissions for example.

A more plausible explanation is that our matched sample is skewed. This is because we use the company name as our identifier to match the *Climate Trace* dataset (observed emissions) to *Refinitiv* dataset (reported emissions). Typically, oil and gas companies are "master brands", i.e. the name of its products carries the name of the company throughout the value chain. The same is true for companies in the Utilities and Materials sectors, which might explain the composition of our matched sample.

Another possible explanation for our results is that *Climate Trace* is overestimating at firm-level. As discussed earlier *Climate Trace* uses a hybrid approach to estimate atmospherically observed emissions, combining a variety of peer-reviewed models that are bespoke to the oil and gas industry[15] (Brandt et al., 2021; Jing et al., 2020). In short, we consider *Climate Trace* to be a more accurate source of firm-level emissions data (Yu et al., 2022; Rutherford et al., 2021) compared to other leading satellite databases/programmes (detailed in Appendix Table A1.)

[14] It is recognised that the U.S. has more private sector oil and gas companies than is typical in other countries where oil and gas assets are often nationalised. The Rystad dataset (a database that covers over 85,000 fields and licenses globally) lists the name of 492 unique owners of oil and gas assets in the U.S. compared to 434 in the rest of the world altogether (Gans et al., 2022).

[15] In 2022 data the Oil Climate Index + Gas (OCI+) model is combined with the Oil Production Greenhouse Gas Emissions Estimator (OPGEE) and the Petroleum Refinery Life-Cycle Inventory Model (PRELIM). OPGEE was developed by the California Air Resources Board and Stanford University (Brandt et al., 2021); PRELIM by the University of Calgary (Jing et al., 2020).

Possibly because of increased accuracy, *Climate Trace* discovered that actual emissions from global oil and gas production were nearly twice the amount reported to the United Nations and that many emissions were unaccounted for in countries that are not obligated to report such data (Gore, 2022). This report is consistent with a study (March 2025) by the Institute for Energy Economics and Financial Analysis (a global institute examining energy markets, trends, and policies), which reported that emissions could be two times higher than reported for oil & gas companies in Australia[16]. The report claims this is largely due to current estimation methods relying only on production-based emissions factors, which may not incorporate comprehensive empirical data, and do not require third-party verification. Additionally, the report notes that companies are not fully utilising 'top-down' methods such as satellite monitoring, remote sensing and flyovers to verify reported emissions and monitor for leaks or plume events (Knight, A.-L. et al., 2025).

A fourth possible explanation is that *Refinitiv Eikon* data is inaccurate. To check the veracity of the *Refinitiv Eikon* dataset, we asked three researcher assistants[17] to manually check each of the 75 under-reporting companies' disclosures in 2022 against those recorded in Annual Report & Accounts, Form 10-K fillings, Sustainability/ESG/CSR reports and company websites available in 2023-24. Each researcher checked and cross-checked 25 companies. In three cases, they found small discrepancies between company disclosures and the *Refinitiv Eikon* data.[18] In each case, company disclosures exceeded *Refinitiv Eikon* data. None of the companies are headquartered in the U.S. and in no cases is this discrepancy sufficient to overturn our conclusion of under-reporting.

The final candidate explanation is that under-reporting is the product of a misalignment of incentives. To explore this possibility, we focus on the 'most-likely' under-reporters i.e. the 33 U.S. energy companies in our dataset and examine (i) regulatory, (ii) financial, (iii) litigation and (iv) reputational incentives in turn.

---

[16] The report also estimated emissions could be three times higher for open-cut coal miners.

[17] Heena Mulchandani, Karan Rakhit and Isabel Ruben (MSc ESG Management students at Kings Business School).

[18] In each case company disclosures exceed *Refinitiv* Scope 1 data for 2022. African Rainbow Minerals Ltd. and Neste Oyj reported Scope 1 & 2. Ring Energy Inc. disclosed 191.09 KtCO2e following acquisition of new production as of 1 June, compared to *Refinitiv* emissions of 124.59 KtCO2e.

Discussion

(i) Regulation poses an insufficient incentive for firms to disclose more accurate GHG emissions

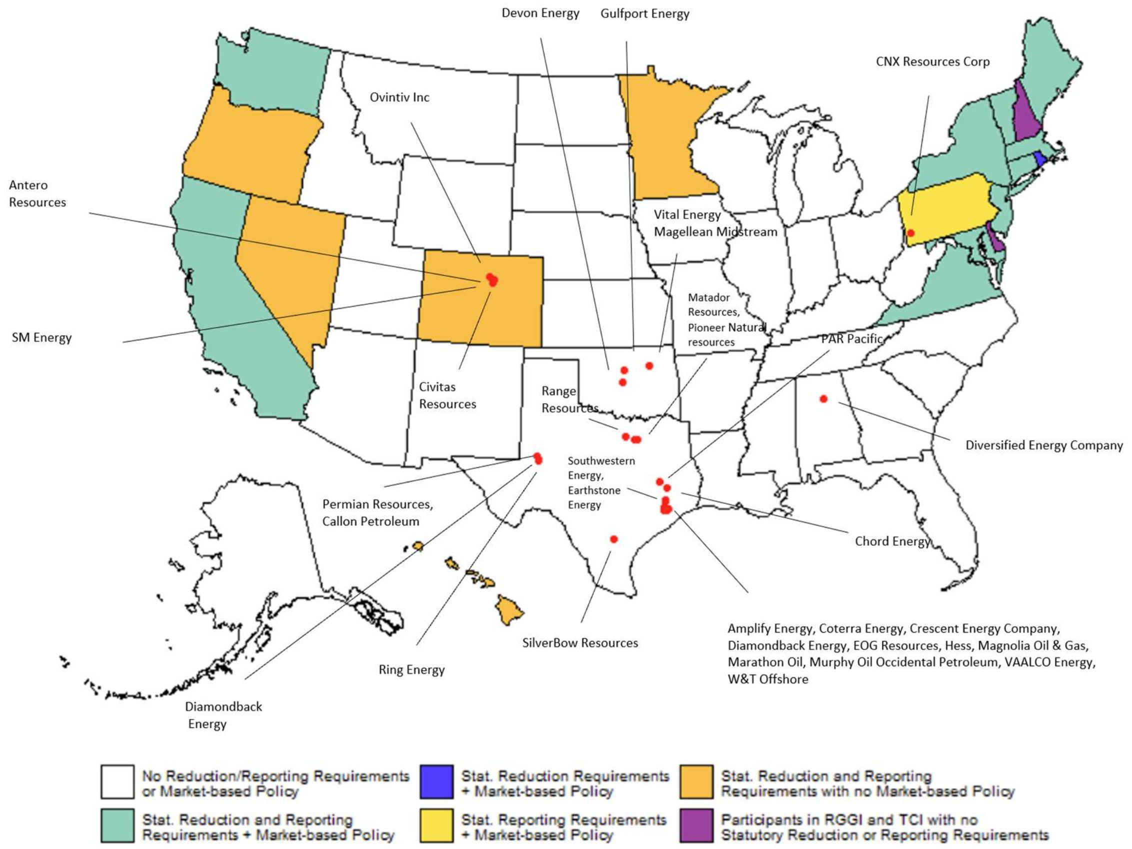
U.S. oil and gas producers are required to submit annual reports of their GHG emissions to the Environmental Protection Agency (EPA) under the Greenhouse Gas Reporting Program (GHGRP) using EPA-approved methods. This mandatory program applies to facilities emitting 25,000 metric tons or more of carbon dioxide equivalent (CO2e) per year[19]. Academic reviews show a positive correlation between company disclosure of GHG emissions mandated by regulation and development of climate strategy at firm-level (Sullivan & Gouldson, 2017).

However, disclosure and strategy do not necessarily translate to emissions reductions unless paired with regulatory or market-based consequences for companies, typically in the form of penalties (Jiang, et al., 2025; OECD, 2023; World Bank, 2021). Market based policies generally take the form of a mandatory emissions trading system (ETS). An ETS (also known as a cap-and-trade scheme) is a market-based policy designed to reduce CO2e emissions by setting a limit (cap) on total emissions and allowing companies to trade emission allowances. Of the 33 under-reporting U.S. energy companies in our dataset, 28 have their headquarters located in States with no additional regulatory GHG reduction or reporting requirements or market-based policies aimed at limiting GHG emissions from major sectors (Figure 2).

This relative absence of regulatory incentives compares with the 11 companies (also categorised in *Climate Trace* as 'oil and gas production and transport') in Group 1 (n=29) whose GHG reports are within 20% of *Climate Trace*. Eight of these over-reporting companies are regulated by a mandatory ETS in Australia (x1), Canada (x2), Japan (x1), Malaysia (x1) and U.K. (x3). The three remaining firms are headquartered in the U.S. in Virginia and Texas (x2) and like all U.S. energy firms are subject to the relatively weak GHGRP. All three oil and gas companies in Group 2 (n = 175) who report GHG emissions greater than *Climate Trace* operate under mandatory ETSs in Australia, U.K. and California.

[19] The GHGRP was established in 2009 and codified at 40 CFR Part 98. As part of the Inflation Reduction Act (2022), the EPA extended GHGRP to include the Waste Emissions Charge (WEC), which penalises methane emissions reported by energy companies exceeding an allowed threshold per facility. The WEC became effective 17 January 2025. However, while the legislative framework for the WEC currently exists, its enforcement was halted when Congress passed a joint resolution disapproving the rule, which President Trump signed on 14 March 2025 rendering the regulation without legal effect.

Figure 2. Location of under-reporting U.S. oil & gas companies



Source: https://www.ncsl.org/energy/greenhouse-gas-emissions-reduction-targets-and-market-based-policies

While our sample is not sufficiently large to make sharp causal statements about the drivers of under-reporting, our results are at least consistent with the notion of weak regulation being an enabling factor which is unlikely to lead to accurate reporting and emissions reductions.

(ii) Financial gains appear to provide insufficient incentives to improve calculation and disclosure

To examine whether under-reporting could be correlated to a lack of financial incentives, it is first necessary to outline the oil and gas production process and associated sources of GHG emissions. All 33-under-reporting oil and gas companies we identify produce natural gas using a process called fracking. Fracking (short for hydraulic fracturing) is a method used to extract oil and natural gas from certain underground rock formations inaccessible by traditional methods. Fracking involves drilling a well vertically and then horizontally into the rock layer (often shale rock) and injecting a mix of water, sand, and chemicals under high-pressure into the well, which cracks the rock, creating tiny fractures which allow gas to flow up to the surface (IEA, 2024).

Natural gas is composed mostly of methane (CH_4) — typically around 85% to 95% by volume depending on the source. The oil and gas industry's CO2e emissions mostly come from burning fossil fuels during the production process and/or from flaring or venting to dispose of unwanted natural gas emitted during production, processing, or transportation. Flaring is the process of burning off excess CH_4 which converts it to carbon dioxide (CO_2) and water vapour, rendering it less potent. Venting is the practice of intentionally or unintentionally (e.g., leaks) releasing CH_4 directly into the atmosphere. The International Energy Agency (IEA) estimates that flaring results in nearly 500 metric tonnes (Mt) of annual CO2e emissions, and that the incomplete combustion of GHGs from flares causes around 10% of methane emissions from oil and gas operations.

It is estimated that up to 80% of oil and gas methane abatement measures could be implemented at a negative or low cost, which theoretically could incentivise improved reporting of GHG emissions as a foundational tool that enables abatement (IEA, 2023)[20]. The costs of methane abatement vary by technology, location, and well type. Estimates range from potential savings of $600 per tonne of CO2e reduced e.g. from leak detection and repair, to costs of $50 per tonne for Reduced Emissions Completions (RECs). RECs is a process in which excess GHG gasses from the production process can be captured rather than flared or vented, separated from fracking fluids, cleaned, shipped and compressed ready for converting into CH_4 which is ready for sale, potentially representing an additional income stream for oil and gas producers (World Bank Global Methane Initiative, 2023).

The estimated value of methane is $100-180 per metric tonne (World Bank Global Methane Initiative, 2023). One tonne of methane (CH_4) contains approximately 52 MMBtu[21] of energy, which is the unit of energy commonly used to calculate natural gas prices. The global wholesale spot price of natural gas is reported by the U.S. Energy Information Administration (EIA) using the benchmark Henry Hub in Louisiana. Table 6. details average natural gas prices for the period 2020-2024 and the corresponding approximate value of methane per tonne.

---

[20] See Annex 3. (Figure A3. Marginal abatement cost curve for methane from oil and gas production, 2023).
[21] MMBtu stands for 'Million British Thermal Units' used in the oil and gas industry to measure the energy content of fuels, especially natural gas.

Table 6. Five-Year Average Natural Gas Prices (2020–2024)

Year	Avg. Price (USD/MMBtu)	Methane Value (USD/tonne CH_4)
2020	$2.03	~$106
2021	$3.89	~$202
2022	$6.45	~$335
2023	$2.53	~$132
2024	$2.19	~$114
Avg.	**$3.42**	**~$178**

Source: (EIA, Henry Hub benchmark)

The average cost of natural gas over this period was $3.42 which converts to an average market value of $178 per tonne of methane, offering only a marginal gain at firm-level when gas prices tend towards $2.00/MMBtu as they did in 2020, 2023 and 2024.

Savings and returns on investments in methane abatement can theoretically incentivise more accurate GHG reporting. However, there are many possible reasons why oil and gas companies are not deploying methane abatement measures. There may be a lack of awareness in the industry regarding the cost-effectiveness of abatement. Costs of RECs appear to be relatively high at $50 per tonne, compared to costs of flaring and/or venting at $15 per tonne. The economics of methane abatement may become progressively unattractive to operators; as methane emissions are reduced, incremental revenue reduces as the volumes of methane captured and sold decrease (LeBlanc, 2024).

The return on investment for methane abatement projects may be over a longer period than for other investment opportunities, which yield more immediate returns in line with financial reporting and dividend[22] cycles. Finally, there may also be a structural barrier to abatement. Oil and gas wells that use fracking have an operational life-expectancy of around five- to six-years (IEA, 2024). This may be insufficient time to achieve a satisfactory return on the investment in the equipment necessary for RECs (i.e. to convert excess GHGs into methane), relative to business-as-usual. This disincentive may be amplified when the well is shuttered, stranding abatement assets used in the REC process and leaving behind sunk costs that cannot be offset by revenues from a new well. In sum, the costs of unilateral action to abate methane emissions relative to incremental revenues can be significant, especially for the relatively smaller oil and gas companies in Group 3.

[22] Shareholders in energy companies normally anticipate a dividend of 3-5% on their investment. Dividends are typically paid from energy company's net profits.

Cost of reporting may act as a disincentive for U.S. oil and gas companies to more accurately report GHG emissions. In preparing its Final Rule extending the GHGRP to include the Waste Emissions Charge (2024)[23], the EPA consulted with oil and gas companies on the incremental cost burden for preparing more accurate GHG reports. For onshore oil and gas producers, such as the 33 under-reporting companies in our sample, original estimates were increased from 15 hours at proposal to 90 hours in the Final Rule. These increased costs represent less than one percent of the total annual revenue for parent entities that would be reporting under the charge (see Annex 4. (Table A2.). While the additional costs of more accurate GHG reporting are not trivial, we can conclude that, at least on their own, they are unlikely to constitute a significant disincentive.

Finally, financial incentives can influence executive decision-making and allocation of resources regarding GHG reporting and reduction. Typically, U.S. executives' remuneration packages include short- and mid-term incentives in the form of bonus payments, triggered on the achievement of performance targets. Such incentives represent the majority of executive pay and generally include a combination of cash payouts and weighted components of stock grants. Some companies include environmental, social and governance (ESG) targets as part of the package structure (Badawi & Bartlett, 2024). In a previous paper Aikman et al., (2023) explored the various ways in which managers can exploit degrees of freedom over methods or datasets to game the GHG Protocol i.e. to achieve ends that are not perfectly aligned with producing an unbiased report of their GHG emissions. This raises the issue of intentionality and the possibility of personal financial incentives for managers of the 33 under-reporting U.S. oil and gas companies in our dataset.

We manually code Form 10-K and Proxy Statements filed in 2023 for financial year 2022. Of the 33 companies analysed, 23 (70%) linked components of executive compensation to health, safety and environmental (HSE) performance. Twelve (52%) of those 23 companies linking ESG performance to executive compensation included quantitative targets focused on GHG emissions (three for methane (CH_4) only). The predominant units of analysis were CO2e, CH_4 and flaring emissions. Performance metrics generally considered emission intensity reductions, as opposed to reductions in absolute levels.

Eleven of the 12 companies linked GHG emissions to short-term cash incentives (i.e. annual bonus payments). Among the 12 companies, emission targets were linked to on average

[23] The WEC became effective 17 January 2025 but has no current legal effect following a resolution by Congress, which President Trump signed on 14 March 2025.

3.19% of named executive officer target compensation[24]. Four companies: CNX Resources Corp., Diversified Energy Company, Range Resources Corp. and Vital Energy Inc. also linked emission reductions to long-term executive compensation.

Evidence from S&P 500 companies for the same 2023 reporting season suggests that executives' achievement of ESG targets, such as GHG emissions reductions, may be assessed less rigorously in the governance process than financial performance. Badawi & Bartlett (2024) report that in 2% of 247 firms reporting on ESG performance executives miss all of their ESG targets, compared to 22% who miss all of their financial targets. The linkage to short- and long-term executive compensation raises at least the theoretical possibility of a financial incentive to under-report GHG emissions.

(iii) Litigation risk reveals a weak incentive for firms to disclose more accurate GHG emissions

Absent regulatory and financial incentives to drive more accurate GHG reporting, this section explores whether risks of litigation can provide an alignment of incentives. Climate-related litigation is increasingly being used as a tool for enforcing corporate and governmental accountability for GHG reporting and climate action. Columbia Law School's Sabin Center for Climate Change Law documents a surge of cases being brought against companies for misrepresentation; of more than 233 new cases filed globally in 2023, 47 were for so-called 'climate washing', bringing the total number of cases involving GHG under-reporting to more than 140 since 2016. Of these 70% have found against the company and been settled in favour of the claimant (Setzer and Higham, 2024). In 2023, a lawsuit *People of the State of California v. Big Oil* was filed against major oil companies, including ExxonMobil, Shell, Chevron, BP, and ConocoPhillips. The suit alleges that these companies deceived the public for decades about the environmental impacts of fossil fuels, contributing significantly to climate change.

U.S. oil and gas companies are mandated to file annual reports of GHG emissions with EPA under the GHGRP. GHGRP data is available to the public via the Facility Level Information on GHG Tool (FLIGHT) to facilitate understanding of possible health effects of pollution from various industrial facilities. Currently, emissions from onshore oil and gas production and distribution are only reported over large areas rather than discrete locations, hindering communities' ability to document adverse health effects or harms caused.

---

[24] Full analysis of individual company compensation packages including performance metrics, weightings etc available on request.

In Texas, North Dakota and Oklahoma, where the majority of under-reporting oil and gas companies in our sample operate, GHGs are emitted during both production and disposal of fracking residue, which includes wastewater and solid waste. Wastewater typically is injected under high pressure into depleted wells or bore holes in a practice known as deep well injection. Solid waste including mud, rock cuttings and sludge are classed as 'non-hazardous' and typically are disposed of in industrial or municipal solid waste landfills[25]. Leaks from deep well injection and landfills emit significant levels of methane (Sobanaa, et al., 2024), which currently goes unreported by producers. One of the stated aims of the Waste Emission Charge was to strengthen the accountability of oil and gas companies to local residents by improving GHG reporting at facility-level and making data available on FLIGHT (EPA, 2024). If the Waste Management Charge ever comes into effect the threat of litigation from local residents and communities could provide an incentive to improved calculation, monitoring and reporting of GHG emissions by U.S. oil and gas companies.

(iv) Reputation risk currently acting as an insufficient incentive

Lastly, we examine whether under-reporting is correlated to weak reputational incentives. Regulators are moving toward requiring companies listed on public stock markets and financial institutions to disclose GHG emissions and other climate-related financial information. The logic follows the principle that improved transparency will expose malfeasant firms to reputational risk and a loss of trust by customers and investors. Loss of customer trust can result in declining sales revenue and damage to brand value (e.g. Chalmers and van den Broek, 2019; Olson et al., 2016) and loss of investor confidence can lead to divestment, shareholder activism, or reduced access to capital (e.g., Ioannou and Serafeim, 2019).

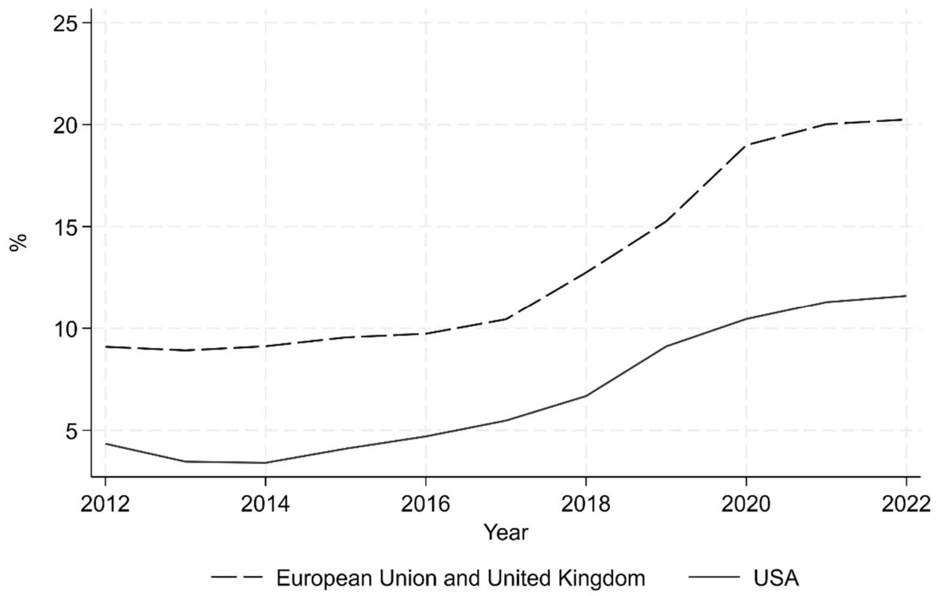
Many of these regulations have come into effect with grace periods during which disclosure remains voluntary (e.g., EU CSRD, IFRS S2)[26] prior to becoming fully effective. In the U.S., the Securities and Exchange Commission proposed a rule mandating disclosure of material climate risks and their financial impacts by publicly listed firms. Shortly after its adoption in March 2024, the rule was challenged and enforcement remains on hold[27], which means company disclosure of GHG emissions remains voluntary.

---

[25] Permitted landfills vary by State.
[26] The European Union's Corporate Sustainability Reporting Directive (CSRD); International Financial Reporting Standards (IFRS) Foundation's Sustainability Disclosure Standard for Climate-related Disclosures.
[27] In February 2025, the SEC announced it was pausing its defence of the rule.

Figure 3. details the share of public companies reporting scope 1 and 2 emissions[28], which is the minimum requirement in the European Union, U.K. and U.S. Approximately 6,000 large 'public interest' companies reported under the EU's Non-financial Reporting Directive (NFRD) for FY 2017. Since then, the rise in voluntary reporting in the three jurisdictions has approximately doubled but remains relatively low at around 20%, suggesting that managers may not regard voluntary reporting as a powerful incentive. The levels of voluntary reporting also help to explain policy aimed at improving the incidence and accuracy of GHG reporting.

Figure 3. The share of public companies reporting Scope 1 and 2 emissions



Notes: This figure includes public companies headquartered in one of the 27 EU countries, the United Kingdom, and the United States. The data series used for this chart are: TR.CompanyMarketCap, TR.CO2DirectScope1, and TR.CO2DirectScope2. Source: *Refinitiv Eikon.*

The U.S. is the world's largest emitter of methane from oil and gas operations measured by methane intensity[29] at 13.3 Mt methane (0.2 CH_4/GJ intensity), followed by the Russian Federation at 11.2 Mt and 0.3 intensity (IEA, 2024). If U.S. energy companies (again, oil and gas producers) continue to systematically under-report as we find, then efforts to improve GHG reporting and reduce methane emissions in the short-term are likely to be retarded. In the absence of a coordinated regulatory framework (Fig. 2.), which includes a powerful financial incentive such as an emissions trading system, firms that invest in improved GHG reporting and

[28] Scope 1 emissions are the direct emissions from sources controlled or owned by the reporting company (from stationary combustion, mobile combustion, physical or chemical processes, and intentional and unintentional releases). Scope 2 emissions arise from the generation of purchased electricity consumed by the company.
[29] Methane emissions intensity is a measure of the methane component of natural gas emissions relative to the methane component of natural gas produced.

methane abatement may face litigation risks and competitive disadvantages relative to peers who choose to free ride on the mitigation efforts of others[30].

4. Under-reporting hides material environmental risk

We have identified 75 companies who are under-reporting primarily in the energy, utilities and materials sectors (see Annex 3). According to the IFRS, *"information is material if omitting, misstating or obscuring it could reasonably be expected to influence investor decisions".* To assess the scale and the material environmental risk of under-reporting, we aggregate the emissions of under-reporting companies in our dataset and compare their emissions to total sector emissions, the latter sourced from the International Energy Agency (IEA)[31]. Results are displayed in Table 4.1.

Column 1 exhibits reported emissions of under-reporting firms, column 2 shows emissions observed by *Climate Trace* and column 3 shows the dissonance. For example, 47 companies belonging to the energy sector under-report their emissions in our dataset; if they reported in line with *Climate Trace,* they would have reported an additional 0.27 Gt of CO2e emissions. Across all sectors, we can see that observed emissions for the 75 companies in Group 3 are more than three times higher than reported emissions.

Table 7. Environmental risk: reported and observed emissions by sector.

Sector	Reported emissions (Co2e Gt)	Observed emissions (Co2eGt)	Emissions dissonance (CO2e Gt)
Energy (n = 47)	0.07	0.34	0.27
Utilities (n = 12)	0.05	0.09	0.04
Materials (n = 11)	0.01	0.03	0.02
Other (n = 5)	0.01	0.01	0.00
All sectors (n = 75)	0.14	0.47	0.33

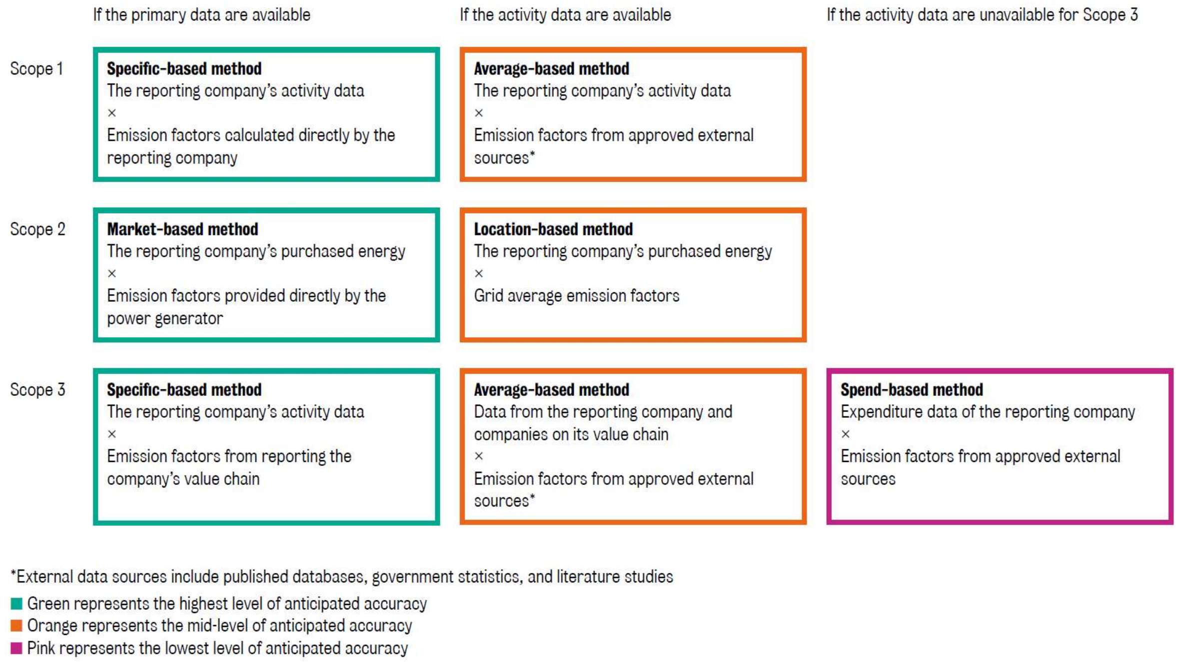
[30] Presenting a classic example of a collective action problem (Olson, 1965).
[31] https://www.iea.org/data-and-statistics

Spillover of under-reporting on value chains

Disclosure of material scope 1, 2 and 3 and total CO2e emissions is required by many regulators including for example the European Securities and Markets Authority (ESMA), California and the IFRS S2 standard, which is currently being adopted in jurisdictions worldwide such as Japan, Canada, Singapore and U.K.. Emissions dissonance has unintended consequences for the calculation of scope 1, 2 and 3 and total CO2e emissions as set out in the GHG Protocol (2105), which can undermine decarbonisation policy.

Scope 1 emissions are the direct emissions from sources controlled or owned by the reporting company (from stationary combustion, mobile combustion, physical or chemical processes, and intentional and unintentional releases). Scope 2 emissions arise from purchased energy consumed by the company. Scope 3 includes all other indirect emissions from the reporting company's upstream and downstream activities[32]. Aikman et al., (2023) summarise a hierarchy of calculation methods under the GHG Protocol reproduced in Figure 4.

Figure 4. Hierarchy of calculation methods under the GHG Protocol

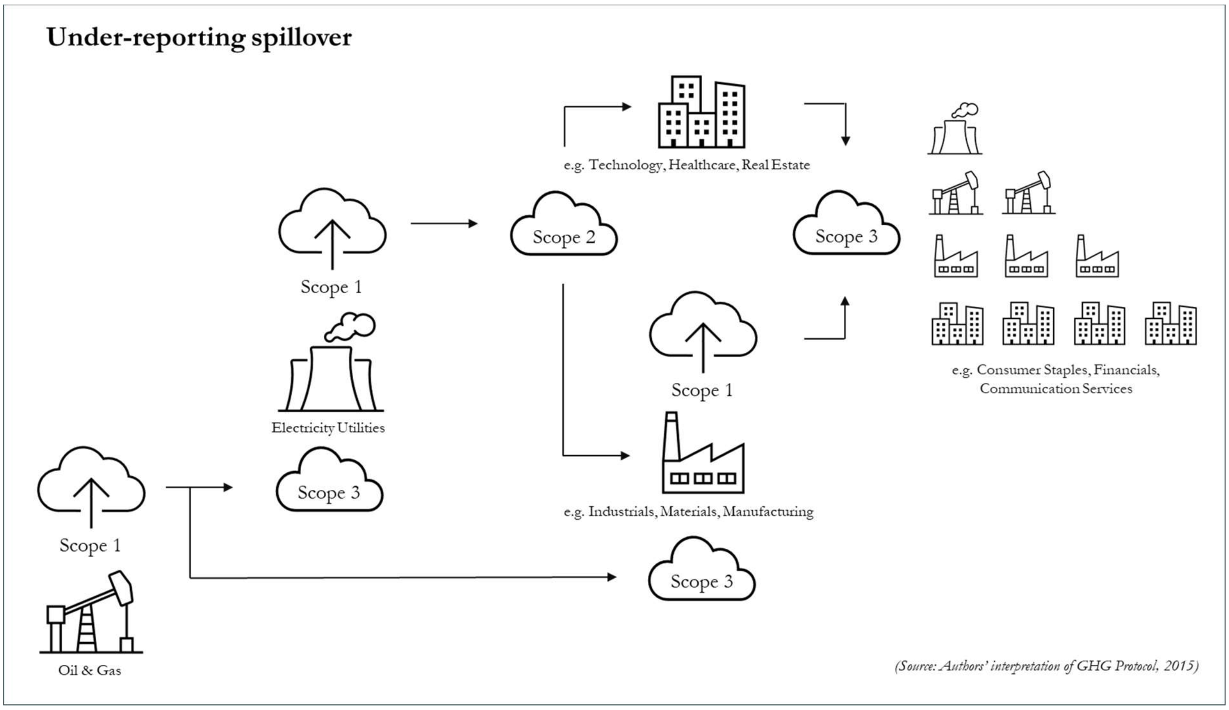


In the case of scope 2 emissions, the Protocol anticipates the highest level of accuracy from the so-called 'market-based' method. Under the market-based method reported emissions

[32] Upstream Scope 3 emissions include those from purchased goods and services, capital goods, fuel- and energy-related activities not included in Scope 1 or 2, upstream transportation and distribution, waste generated in operations, business travel, employee commuting, and upstream leased assets. Downstream Scope 3 emissions include those from transportation and distribution, processing of sold products, use of sold products, end-of-life treatment of sold products, leased assets, franchises, and investments.

by electricity suppliers can be used by preparers to generate a company-specific emission factor for scope 2 which is deemed by the Protocol to be more reliable than industry averages used in the location-based method provided by approved external sources, including grid average emissions. For scope 1 and scope 3 the Protocol prioritises the 'specific-based' method over industry averages used in the 'average-based' method and additionally, in the case of scope 3 the 'spend-based' method using approved external sources[33]. In line with the concept of emissions intensity (Ehlers, et al., 2020) a company-specific emission factor is calculated by dividing reported total CO2e emissions by company revenue to derive a spend-based emission factor i.e. X tCO2e per dollar of revenue. Although not sanctioned by the GHG Protocol (2015) spend-based emission factors derived in this manner are also frequently used by preparers to calculate scope 1 emissions (Aikman, et al., 2023). Oil and gas are a primary factor of production, which amplifies the potential spillover of under-reporting by energy companies to energy utilities and other customers. This spillover effect is detrimental to the calculation of firm- and sector-level emissions throughout the economy and undermines policy (Fig. 5).

Figure 5. Spillover effects of under-reporting



[33] Approved sources include open databases (e.g., IPCC Emissions Factor Database), government statistics (e.g., UK-Defra and US-EPA), literature studies, and industry associations. The lowest level of anticipated accuracy is provided by using so-called 'Environmentally Extended Input-Output' or EEIO models, which combine data from input-output tables which allocate national GHG emissions to different finished products or specific industries based on economic transactions between sectors (WRI and WBCSD, 2011).

We use electricity utilities, who purchase oil and gas from under-reporting companies, as an example to illustrate the spillover effect of under-reporting. Such electricity utilities, using the spend-based method to calculate their scope 3 emissions (under category 3.3 'fuel & energy'), are by default, under-reporting their total emissions. Customers of those electricity utilities (e.g. in technology, healthcare or real estate), wishing to report as accurately as possible and therefore using company-specific emission factors are, by default, under-reporting their scope 2 emissions. GHG emitted in the provision of their products and services are then consumed throughout the economy in the form of scope 3 'purchased goods & services'. In the same way, customers (e.g. industrials, materials, manufacturing) purchasing oil and gas directly from under-reporting suppliers will be under-reporting their scope 3 emissions, and depending on how they use the fuel, will also potentially under-report total emissions, which become their customers' scope 3. It is estimated that scope 3 emissions account for over 80% of overall carbon emissions of companies (Fouret, et al., 2024).

Contrary to the highest levels of accuracy anticipated by the GHG Protocol, such amplification of emissions dissonance unintentionally contaminates GHG emissions data; damages efforts to price physical and transition risk into investment appraisal; and undermines decarbonisation policy.

5. Conclusion and Policy Recommendation

Our study matches data from *Climate Trace* with company specific data from *Refinitiv Eikon* to compare observed scope 1 CO2e emissions with reported emissions at firm-level. We obtain an accurate match of 279 companies, for which both observed and reported emissions are available and divide them into three groups: (1) companies for which there is an equivalence between reported and observed emissions (±20%); (2) companies whose reported emissions are higher than observed; and (3) companies for whom observed emissions are higher than reported. The 75 under-reporting companies in Group 3 are (i) generally smaller (albeit by no means small) in terms of revenue, market capitalization, and number of employees than are firms in the full sample (ii) are less frequently audited for Corporate Social Responsibility matters such as GHG reporting; (iii) operate primarily in the energy, utilities and materials sectors; and (iv) are headquartered mainly in North America (but also in Europe and to a lesser extent Asia).

Emissions dissonance is widespread in the energy sector, where it is 21.92% more likely that a company will underreport its emissions. We identify 47 under-reporting energy companies whose reported emissions represent 2.85% of total energy sector emissions as reported by the

IEA (2023). If under-reporting energy companies reported in line with emissions observed by *Climate Trace* their emissions rise to 0.27 Gt. Contrary to the highest levels of accuracy anticipated by the GHG Protocol, customers of under-reporting companies using company-specific data may unintentionally suffer a spillover effect in estimating their own scope 2, 3 and total CO2e emissions.

Policy recommendation

We provide fresh evidence on the scale of inaccuracies in reported GHG emissions to suggest that while reporting by companies may be necessary, it is unlikely ever to be a sufficient basis for policy. We find that firms lack regulatory, financial, litigation and reputational incentives to improve the accuracy of their GHG calculation and reporting (Jiang, et al., 2025).

Our findings support calls for a coordinated regulatory framework which includes policy tools like carbon pricing, subsidies for clean tech, regulation, and enforcement (OECD, 2023; World Bank, 2021). Such calls are further supported by evidence of a 26% fall in methane emissions for 2023 compared to 2022 (the period of our dataset) in the Permian Basin of Texas and New Mexico, where the majority of our most-likely under-reporting companies operate (LeBlanc, 2024). This fall is largely attributed to oil and gas companies' response to the EPA's planned introduction of the Waste Emissions Charge (WEC)[34], part of the Inflation Reduction Act (2022) (McCormick, 2024). Under the WEC Methane emissions exceeding specified thresholds would be subject to a charge starting at $900 per metric ton of reported methane emissions for 2024, increasing to $1,200 per metric ton for 2025 emissions, and $1,500 per metric ton for emissions years 2026 and later[35] (EPA, 2024).

To conclude the paper, we recommend the default use of advanced measurement data from satellite and remote sensing technologies by policymakers to automatically observe annual methane (CH_4) emissions from oil and gas facilities, apportioned and aggregated to companies based on the companies operational share of each facility (GHG Protocol, 2015)[36], a policy we term 'default emissions'. Default emissions are observed measures of oil and gas company annual methane ($DefCH_4$) in metric tonnes (Mt) over 100 years of global warming potential. A policy of $DefCH_4$ is akin to methods deployed in many countries for the collection of income taxes. For example, in the U.K. HM Revenue & Customs (HMRC) estimates taxes owed and invites

[34] See: https://www.epa.gov/inflation-reduction-act/waste-emissions-charge
[35] Federal Register/Vol. 89, No. 222/Monday, November 18, 2024/Rules and Regulations
[36] Known as the 'Operational Control' method of apportioning GHG emissions (GHG Protocol, 2015).

individuals to provide data to correct and adjust year-end estimates as required, resulting in additional payments (and/or penalties) to make up any deficit or refunds[37].

In a similar manner, policymakers would invite companies to adjust their DefCH_4 estimate to reflect changing circumstances or information as necessary (akin to self-assessment of income tax) using approved methods in accordance with IFRS sustainability reporting standards for the year-end reconciliation (AdjCH_4). Alternatively, material discrepancies could automatically trigger on-site checks and audits.

Linking self-reporting to IFRS standards helps to drive standardisation and integration of GHG emissions data with financial reporting. Year-end DefCH_4 or AdjCH_4 would be *de facto* emissions data for companies, replacing (in large part) self-reported data currently lacking standardisation. Both designations would signal regulatory approval creating a global baseline of methane emissions data for oil and gas companies and mitigating against greenwashing (IFRS 2024). AdjCH_4 represents an opportunity for companies to build trust among stakeholders. Company AdjCH_4 (bottom-up) combines with DefCH_4 (top-down) to generate improved calculation, monitoring and reporting requirements and methods that helps to narrow estimation of methane emissions over time (Cenci & Biffis, 2025). Without such standardisation, there is a risk that the levels of under-reporting we find could (continue to) to be vulnerable to gaming as economic and political incentives grow (Aikman, et al., 2023), contaminate financial data misleading investors and distorting capital allocation, and undermine policy aimed at methane reduction.

DefCH_4, would be calculated via a platform of top-down technologies governed by the International Methane Emissions Observatory (IMEO) as the global source of CO2e emissions truth. The IMEO is a United Nations Environment Programme (UNEP) initiative established to provide open, reliable, and actionable data to policymakers, firms and individuals, "with the authority to reduce methane emissions" (UNEP, 2024). IMEO deploys satellite monitoring as part of its Methane Alert and Response System (MARS) to detect major methane emissions data providing near-real-time alerts to stakeholders. IMEO is chosen in part because of its focus on methane, which as noted is the "fastest, most cost-effective way to slow the current rate of warming" (UNEP, 2024).

MARS employs a "tip-and-cue" methodology that integrates data from various satellite instruments. Initially, broad-area satellites like TROPOMI (see Annex 1) identify regions with

[37] HMRC estimates tax owed using previous income history, employer and pension provider reports (in real time), benefits received (e.g., company car) and tax code adjustments for under/overpayments.

elevated methane concentrations. Subsequently, additional high-resolution satellites are tasked to pinpoint specific emission sources within these regions. This approach enables MARS to detect and attribute methane emissions to individual facilities when conditions allow (UNEP, 2025). Conceptually, MARS could be augmented by *Climate Trace* and new, not for profit technologies as they emerge. A system, such as MARS, of top-down satellite and remote sensor monitoring technologies benefits from network effects i.e. the value of the system increases as more policymakers use it. Once deployed, additional jurisdictions can be added at minimal cost and the system's value increases exponentially with scale – each new jurisdiction extends coverage and enhances the entire system's effectiveness through better triangulation. A system of co-ordinated, pan-regional or global triangulation could also help to inoculate monitoring systems from opportunistic economic and/or political incentives.

DefCH_4 creates a level-playing field – any inaccuracies in measurement are wrong in the same way for all market participants, both within and across jurisdictions. DefCH_4 and AdjCH_4, would create a standardised dataset providing consistency and comparability at firm- industry- and geographical-level. Such standardisation (i) enables the integration of methane emissions data with financial data (ii) facilitates more accurate pricing of risk by insurance and capital markets; (iii) offers opportunities for firms to build stakeholder trust, attract capital, and enhance long-term value; and (iv) incentivises firms to integrate methane reduction targets into their strategic and financial planning to mitigate risk and foster resilience in their supply chains.

Adoption of DefCH_4 echoes policymakers' calls for the use of top-down methodologies aimed at making the calculation of GHG emissions and their reporting robust (e.g., California Air Resources Board, 2025; European Commission, 2024; UN, 2023; IPCC, 2022). DefCH_4 could be scaled to include (a) carbon equivalent emissions (DefCO2e and AdjCO2e) (b) additional high emitting sub-sectors such as steel, cement, materials & mining, chemicals, manufacturing; and (c) extend policy to include high emitting facilities operated by private companies. Such an extension would disincentivise the sale of high-emitting assets by publicly quoted firms to private companies, such as private equity and hedge funds[38], currently outside reporting scope (Gözlügöl & Ringe, 2022).

[38] A practice known as 'brown spinning' (Gözlügöl & Ringe, 2022)

Annex 1. Probit regression

Table A1. Probit regression

	(1)	(2)
Emission	-0.36***	-0.35***
	(0.07)	(0.07)
Size	-0.16*	-0.15*
	(0.09)	(0.09)
Energy	1.14***	0.71**
	(0.23)	(0.27)
US	0.72***	-0.36
	(0.26)	(0.52)
CA	-0.14	-0.05
	(0.31)	(0.30)
Not audited	-0.06	-0.06
	(0.23)	(0.24)
Energy & US		1.79***
		(0.62)
Constant	7.68***	7.38***
	(2.00)	(2.04)
Observations	279	279
Pseudo R^2	0.41	0.44

Note *p < 0.10, **p < 0.05, ***p < 0.01.
Missing (log) revenues values are replaced by the (log) of market capitalization.

Annex 2. Observed emissions: state of the art.

Observed emissions (also referred to as top-down) are founded on methodologies operating at a regional scale and relying on atmospheric observations of GHGs and inverse modelling (Deng et al., 2022). Top-down approaches typically rely on in-situ measurements or remote sensing data from satellite observations, ground-based stations, or aerial observations (German, Matthews, & Ruyssenaars, 2021). By analysing variations and changes in atmospheric GHG concentrations near individual facilities, this method uses inverse modelling to trace GHGs back to their sources (Fung, et al., 2023; Flerlage, Velders, & Boer, 2021; Vaughn, et al., 2018). By simulating how emissions would spread in the atmosphere, inverse modelling iteratively adjusts the estimates until they align with the observed concentrations, effectively tracing the emissions back to their most likely sources (Bergamaschi, et al., 2018).

Satellites have revolutionized the way we can measure and track greenhouse gas emissions. Satellites like the European Space Agency's Copernicus Sentinel-5P (Veefkind, et al., 2012) and NASA's Orbiting Carbon Observatory-2 (OCO-2) (Crisp, et al., 2004) use spectroscopic techniques to measure key greenhouse gases like CO_2 and CH_4 in the atmosphere. These systems can provide near-real-time data that allows for continuous tracking of emissions over large regions[39]. Table A1. highlights the diverse capabilities and focuses of leading databases in monitoring GHG emissions globally.

Table A2. Comparison of leading satellite databases in monitoring GHG emissions.

Database/ Program	GHGs Covered	Spatial Resolution	Temporal Resolution	Coverage	Type	Notes
Copernicus Atmosphere Monitoring Service (CAMS)	CO_2, CH_4, CO	0.1° x 0.1° (global)	5-day forecasts; reanalysis from 2003–2020	Global	Top-down modelling using satellite and in-situ data	Provides observation-based information supporting the Paris Agreement.
EDGAR (Emission Database for Global Atmospheric Research)	CO_2, CH_4, N_2O, others	0.1° x 0.1°	Annual; with monthly and hourly profiles	Global	Bottom-up inventory with some top-down integration	Provides gridded emissions data for policy and research.

[39] NASA's Carbon Monitoring System (CMS) and Earth Surface Mineral Dust Source Investigation (EMIT) (Thorpe, et al., 2023) mission also contribute to detecting greenhouse gas emissions from the space.

TROPOMI on Sentinel-5P	CH_4, CO, NO_2, others	5.5 km x 7 km (post-Aug 2019)	Daily	Global	Satellite-based spectrometry	High spatial resolution; effective for detecting methane emissions.
NASA's OCO-2 and OCO-3 Missions	CO_2	~1.3 km² per pixel	OCO-2: 16-day repeat cycle; OCO-3: variable, with snapshot area mapping	Global (OCO-2); Targeted (OCO-3)	Satellite-based spectrometry	High-resolution measurements aiding in tracking CO_2 sources and sinks.
GOSAT (Greenhouse Gases Observing Satellite)	CO_2, CH_4	10.5 km diameter footprint	Revisits every 3 days	Global	Satellite-based spectrometry	First satellite dedicated to GHG monitoring; provides data for climate research.
GHGSat	CH_4, CO_2	~25 m	Targeted revisits; frequency depends on tasking	Targeted industrial sites	Commercial satellite-based	Monitors emissions from individual facilities; high-resolution data.
Climate TRACE	CO_2, CH_4, N_2O, PM2.5, others	Asset-level (varies by sector)	Monthly; aiming for near real-time	Global	Aggregated satellite, remote sensing, and AI-based analysis	Independent emissions tracking; enhances transparency.

Notes:

- **Spatial Resolution:** Refers to the size of the area each data point represents.
- **Temporal Resolution:** Indicates how frequently data is updated or available.
- **Coverage:** Describes the geographical extent of the data collection.
- **Type:** Specifies the method of data collection, such as satellite-based measurements or modelling approaches.

An increasing number of empirical studies are adopting observed, top-down estimates, moving away from reliance on reported, bottom-up emission inventories. For instance, researchers at World Bank developed an urban CO_2 emissions model using satellite-measured CO_2 concentrations from 2014 to 2020, covering more than a thousand cities. Their findings reveal that economic development significantly influences the relationship between population density and CO_2 emissions (Dasgupta, Lall, & Wheeler, 2021). In another study, researchers used data from the OCO-2 satellite to provide the first independent estimates of direct per capita CO_2 emissions for 20 cities across multiple continents. This study also examined the relationship between CO_2 emissions and population density (Wu, et al., 2020). In the remainder of this section, we review studies that applied observed (top-down) emission monitoring methodologies to verify the reported (bottom-up) emission inventories, i.e., the methodology we adopt.

A wealth of research compares top-down estimates with reported emissions at the regional or national level. Deng et al., (2022), for example, developed a comprehensive framework to compare GHG data from inversion models with national greenhouse gas inventories (NGHGIs) submitted to the United Nations Framework Convention on Climate Change (UNFCCC). They found that the median CO_2 estimates from the models suggest that temperate regions in the Northern Hemisphere, such as Russia, Canada, and the European Union, absorb more CO_2 through carbon sinks (e.g., forests and soils) than what is reported in their NGHGIs. They also found that methane (CH_4) emissions, particularly from oil- and gas-producing regions in the Persian Gulf, Central Asia, and parts of Russia, are underreported compared to the inversion results. Similarly, nitrous oxide (N_2O) emissions in tropical countries, Mexico, and Australia are also significantly underreported.

Recent studies have also uncovered significant discrepancies between satellite-derived emission estimates and self-reported data from the oil and gas sector. For example, Climate TRACE discovered that actual emissions from global oil and gas production were nearly twice the amount reported to the United Nations. Additionally, many emissions were unaccounted for in countries that are not obligated to report such data (Gore, 2022).

At regional level, research has examined total anthropogenic methane emissions (from oil and gas, agriculture, and waste) in Alberta and Saskatchewan from 2010 to 2017. Using inversion modelling and atmospheric CH_4 observations from four monitoring sites, researchers estimated an annual anthropogenic emission rate of around 3.7 $MtCH_4$ per year, which was approximately 60% higher than the figure reported in Canada's National Inventory Report (NIR). This discrepancy is primarily due to oil and gas sector emissions, of which the resulting estimate is nearly twice that reported in Canada's NIR (Chan, et al., 2020). Another airborne study also measured the methane emissions from oil and gas infrastructure in Alberta. The results suggest that reported venting emissions in this province are likely underestimated by a factor of 2.5. Additionally, total CH_4 emissions from Alberta's upstream oil and gas sector can be 25–50% higher than current government estimates (Johnson, et al., 2017).

Extensive research has also examined methane emissions in the US oil and gas sector. One study integrated data from approximately one million aerial site measurements into emissions inventories for six regions in the US, covering 52% of onshore oil and 29% of gas production, across 15 aerial campaigns. The researchers estimated the CH_4 loss rates [40] for each region, with

[40] The emitted fraction of methane produced from oil and natural gas activity in a given region.

the six-region weighted average equal to 2.95%—roughly three times the national government inventory estimates by US Environmental Protection Agency (EPA) in 2022 (Sherwin, et al., 2024). Another study also focuses on the methane emissions from US oil and natural gas supply chain. It estimates based on ground-based facility measurements validated with aircraft observations, and estimates 2015 are about 60% higher than the EPA's inventory estimate for that year (Alvarez, et al., 2018).

Annex 3. Under-reporting companies (Group 3)

ID	Name Refinitiv	ISO3 country	GICS sector	CO2e emissions Refinitiv (Kt)	Name Trace	CO2e emissions Trace (Kt)	Installation name Trace	CO2e emissions inst. Trace (Kt)	% of interest
1	ARC Resources Ltd	CAN	10	1828.00	Arc Resources	9228.20	Montney AB	13617.77	43.37
1							Peace River	929.24	1.43
1							Montney BC	19637.35	16.85
2	African Rainbow Minerals Ltd	ZAF	15	418.03	African Rainbow Minerals	1452.55	Impunzi Complex	736.85	20.20
2							Mogalakwena Mine	671.45	100.00
2							Goedgevonden Coal Mine	637.87	26.00
2							Tweefontein Coal Mine	966.70	20.20
2							Kroondal Mine	271.13	100.00
3	Aker BP ASA	NOR	10	1066.46	Aker BP	2413.82	Aerfugl	2413.82	100.00
4	Amplify Energy Corp	USA	10	211.65	Amplify Energy	341.71	East Texas	14889.11	1.69
4							Haynesville	68682.19	0.00
4							Green River	10062.11	0.86
5	Ampol Ltd	AUS	10	729.08	Ampol	1130.82	Ampol Lytton Refinery	1130.82	100.00
6	Anglo American Platinum Ltd	ZAF	15	540.00	Anglo American Platinum	1300.75	Palabora Mine	335.60	100.00
6							Modikwa Mine	95.49	100.00
6							Bafokeng-Rasimone Mine	95.99	100.00
6							Pilanesberg Mine	25.56	100.00
6							Marula Mine	78.80	100.00
6							Dishaba Mine	100.08	100.00
6							Tumela Mine	108.42	100.00
6							Impala Mine	382.24	100.00
6							Styldrift 1 Mine	78.57	100.00
7	Antero Resources Corp	USA	10	243.99	Antero Resources	18033.90	Other Appalachia	11132.03	0.02
7							Marcellus	145846.30	11.30
7							Utica	29174.46	5.33
8	Bangchak Corporation PCL	THA	10	932.12	Bangchak	1439.23	Bangchak Petroleum Ref.	1439.23	100.00
9	Birchcliff Energy Ltd	CAN	10	348.41	Birchcliff Energy	2859.78	Montney AB	13617.77	21.00
10	CNX Resources Corp	USA	10	559.36	CNX Resources Corporation	8111.57	Other Appalachia	11132.03	0.41
10							Marcellus	145846.30	5.09
10							Utica	29174.46	2.21
11	CTCI Corp	TWN	20	5.50	CTCI	187.00	Kuo Kuang power station	935.00	20.00
12	Callon Petroleum Co	USA	10	824.92	Callon Petroleum	3693.72	Eagle Ford - black oil	16971.16	4.07
12							Permian TX	216085.20	1.39
13	Capstone Copper Corp	CAN	15	389.31	Capstone Copper	2218.17	Los Pelambres Mine – (CHL)	249.84	100.00
13							Charcas Mine – (MEX)	18.58	100.00
13							Los Bronces Mine – (CHL)	1949.75	100.00
14	Central Puerto SA	ARG	55	6450.68	Central Puerto	10747.97	Brigadier Lopez	453.00	100.00
14							Costanera power station	4755.00	100.00
14							Manuel Belgrano I	1214.00	10.83
14							Vuelta De Obligado	1212.00	56.19
14							Timbu´es power station	1307.00	9.60
14							Puerto power station	3609.00	100.00
14							Lujan De Cuyo	993.00	100.00
15	Champion Iron Ltd	CAN	15	93.94	Champion Iron	750.26	Bloom Lake Mine – (CAN)	750.26	100.00
16	Chord Energy Corp	USA	10	1588.77	Chord Energy	4575.98	Anadarko	34366.04	0.00
16							Bakken-US	42372.34	10.80
16							East Texas	14889.11	0.00
17	Civitas Resources Inc	USA	10	1250.80	Civitas Resources	5202.09	Denver Julesburg	29708.35	17.51
18	Contact Energy Ltd	NZL	55	656.73	Contact Energy	1125.00	Stratford power station	994.00	100.00
18							Whirinaki power station	131.00	100.00
19	Coronado Global Resources Inc	AUS	15	2112.13	Coronado Global Resources	6260.24	Buchanan #1 Coal Mine – (USA)	1968.28	100.00
19							Muddy Bridge Coal Mine – (USA)	220.52	100.00
19							Mountaineer Pocahontas – (USA)	15.21	100.00
19							Powellton #1 Coal Mine – (USA)	163.49	100.00
19							Curragh Coal Mine	3642.46	100.00
19							Lower War Eagle Coal Mine – (USA)	171.09	100.00
19							Kuhn Ridge Coal Mine – (USA)	79.18	100.00
19							Logan Coal Complex – (USA)	0.00	100.00
20	Coterra Energy Inc	USA	10	1546.92	Coterra Energy	23943.66	Marcellus	145846.30	8.66
20							Anadarko	34366.04	4.28
20							Arkoma	10625.29	0.01
20							Permian NM	88652.74	2.17
20							Permian TX	216085.20	3.66
21	Crescent Energy Co	USA	10	1123.25	Crescent Energy	2896.92	Barnett	17234.32	4.74
21							Uinta	11524.30	8.30
21							Eagle Ford - black oil	16971.16	1.34
21							Permian TX	216085.20	0.27
21							Powder River	5944.23	3.91
21							Permian NM	88652.74	0.09
22	Devon Energy Corp	USA	10	4590.00	Devon Energy	20868.32	Powder River	5944.23	8.25
22							Anadarko	34366.04	6.53
22							Austin Chalk	7572.11	1.80
22							Eagle Ford - black oil	16971.16	3.27
22							Eagle Ford - volatile oil	8277.93	2.19
22							Permian TX	216085.20	2.68
22							Permian NM	88652.74	10.98
22							Bakken-US	42372.34	4.09

ID	Name Refinitiv	ISO3 country	GICS sector	CO2e emissions Refinitiv (Kt)	Name Trace	CO2e emissions Trace (Kt)	Installation name Trace	CO2e emissions inst. Trace (Kt)	% of interest
23	Diamondback Energy Inc	USA	10	1487.28	Diamondback Energy	14829.04	Permian TX	216085.20	6.86
24	Diversified Energy Co	USA	10	1820.00	Diversified Energy Company	5956.75	Haynesville	68682.19	0.46
24							Barnett	17234.32	4.95
24							East Texas	14889.11	9.48
24							Other Appalachia	11132.03	17.67
24							Utica	29174.46	1.33
24							Other Appalachia - coal bed methane	650.22	13.45
24							Anadarko	34366.04	0.54
24							Marcellus	145846.30	0.52
25	ENGIE Energia Chile SA	CHL	55	3600.00	ENGIE Energ´ıa Chile	4961.00	Andina-Hornitos power station	1547.00	100.00
25							Mejillones power station	3414.00	100.00
26	EOG Resources Inc	USA	10	5100.00	EOG Resources	29510.37	Denver Julesburg	29708.35	0.85
26							Utica	29174.46	0.12
26							Eagle Ford - dry gas	7626.86	3.67
26							Anadarko	34366.04	0.64
26							Austin Chalk	7572.11	14.31
26							Powder River	5944.23	18.79
26							Bakken-US	42372.34	1.68
26							Barnett	17234.32	4.92
26							Permian TX	216085.20	2.58
26							Eagle Ford - black oil	16971.16	31.31
26							Permian NM	88652.74	15.89
27	ERG SpA	ITA	55	0.94	ERG	529.00	Priolo-Melili power station	408.00	100.00
27							NuCe Sud power station	121.00	100.00
28	EVN AG	AUT	55	1072.86	EVN	2541.97	Theiss power station	801.00	100.00
28							Duisburg-Walsum power S. – (DEU)	3553.00	49.00
29	Earthstone Energy Inc	USA	10	515.01	Earthstone Energy	3760.94	Permian TX	216085.20	1.15
29							Permian NM	88652.74	1.41
29							Eagle Ford - black oil	16971.16	0.15
30	Enel Generacion Peru SAA	PER	55	1467.06	Enel Generaci´on Peru´	1977.00	Santa Rosa power station	1210.00	100.00
30							Ventanilla power station	767.00	100.00
31	Enerplus Corp	CAN	10	838.20	Enerplus Corporation	1853.63	Denver Julesburg – (USA)	29708.35	0.15
31							Bakken-US – (USA)	42372.34	4.27
32	Eneva SA	BRA	55	2681.40	Eneva	6309.60	Porto do Pec´em power station	5956.00	33.64
32							Parnaiba power station	2330.00	100.00
32							Itaqui power station	1976.00	100.00
33	Ero Copper Corp	CAN	15	42.10	Ero Copper	216.91	Sossego Mine – (BRA)	209.99	100.00
33							Santa Rita Mine – (BRA)	0.00	100.00
33							Pedra Branca Mine – (BRA)	6.93	100.00
34	Fortuna Silver Mines Inc	CAN	15	80.97	Fortuna Silver Mines	114.38	Lindero Mine – (ARG)	114.38	100.00
35	Gibson Energy Inc	CAN	10	107.23	Gibson Energy	266.54	Gibson Energy Moose Jaw Refinery	266.54	100.00
36	Gulfport Energy Corp	USA	10	290.61	Gulfport Energy	4617.73	Uinta	11524.30	0.04
36							Anadarko	34366.04	4.40
36							Utica	29174.46	10.63
37	Hess Corp	USA	10	2231.00	Hess	4310.25	Bakken-US	42372.34	10.17
38	Hokkaido Electric Power Company	JPN	55	12525.00	Hokkaido Electric Power	22656.97	Shiriuchi power station	477.00	100.00
38							Date power station	477.00	100.00
38							Toyama Shinko power station	3665.00	30.04
38							Sunagawa power station	1423.00	100.00
38							Onbetsu power station	101.00	100.00
38							Ishikariwan Shinko power station	834.00	100.00
38							Nanao-Ota Shinko power station	4585.00	100.00
38							Tomatouatsuma power station	9393.00	100.00
38							Tsuruga power station	4095.00	100.00
38							Tomakomai power station	171.00	100.00
39	Jaiprakash Power Ventures Ltd	IND	55	6913.61	Jaiprakash Power Ventures	17937.39	Bara Thermal Power Project	9355.00	100.00
39							Amelia North Coal Mine	70.39	100.00
39							Jaypee Nigrie Super Thermal	6338.00	100.00
39							Bina Thermal Power Project	2174.00	100.00
40	Lubelski Wegiel Bogdanka SA	POL	10	48.11	Lubelski Wegiel Bogdanka	4867.54	LW Bogdanka Coal Mine	4867.54	100.00
41	Lundin Mining Corp	CAN	15	455.14	Lundin Mining	1032.06	Copper Cities Mine – (USA)	0.00	100.00
41							Candelaria Mine – (CHL)	183.60	100.00
41							Aripuana Mine – (BRA)	1.29	100.00
41							Minera Valle Central Mine – (CHL)	657.50	100.00
41							Kristineberg Mine – (SWE)	14.76	100.00
41							Andina Mine – (CHL)	174.92	100.00
42	Magellan Midstream Partners LP	USA	10	209.35	Magellan Midstream Partners	264.23	Magellan Terminal Holdings LP	264.23	100.00
43	Magnolia Oil & Gas Corp	USA	10	445.32	Magnolia Oil & Gas	2006.41	Eagle Ford - black oil	16971.16	3.60
43							Austin Chalk	7572.11	18.44
44	Malakoff Corp Bhd	MYS	55	16816.80	Malakoff Corporation	21861.12	Prai power station	703.00	100.00
44							Lumut SEV power station	2938.00	87.58
44							Tanjung Bin power station	17556.00	100.00
44							Sultan Aziz power station	9866.00	10.43
45	Marathon Oil Corp	USA	10	3170.00	Marathon Oil	14131.65	Austin Chalk	7572.11	2.70
45							Barnett	17234.32	1.14
45							Eagle Ford - volatile oil	8277.93	38.16
45							Eagle Ford - condensate	14932.12	7.06
45							Permian NM	88652.74	0.91
45							Anadarko	34366.04	2.77
45							Alba – (GNQ)	4541.93	100.00
45							Bakken-US	42372.34	7.44
45							Eagle Ford - black oil	16971.16	0.37

ID	Name Refinitiv	ISO3 country	GICS sector	CO2e emissions Refinitiv (Kt)	Name Trace	CO2e emissions Trace (Kt)	Installation name Trace	CO2e emissions inst. Trace (Kt)	% of interest
46	Matador Resources Co	USA	10	973.87	Matador Resources	4550.54	East Texas	14889.11	0.07
46							Permian NM	88652.74	4.47
46							Haynesville	68682.19	0.17
46							Eagle Ford - black oil	16971.16	0.30
46							Permian TX	216085.20	0.19
47	Mitsui & Co Ltd	JPN	20	353.25	Mitsui & Co	1650.98	Kwinana Refinery cogen. – (AUS)	123.00	35.00
47							Al-Dur Power and Water S. – (BHR)	6214.00	16.51
47							Greenfield Energy Centre – (CAN)	1164.00	50.00
48	Murphy Oil Corp	USA	10	1056.51	Murphy Oil	2360.99	Eagle Ford - condensate	14932.12	0.59
48							Eagle Ford - black oil	16971.16	4.44
48							Eagle Ford - volatile oil	8277.93	3.31
48							Montney BC (CAN)	19637.35	6.05
48							Austin Chalk	7572.11	0.77
49	Neste Oyj	FIN	10	2075.00	Neste	2744.69	Neste Porvoo Refinery	2744.69	100.00
50	Newmont Corporation	USA	15	1730.57	Newmont	4812.57	Morenci Mine	1762.80	100.00
50							Boddington Mine – (AUS)	2086.30	100.00
50							Toquepala Mine – (PER)	963.46	100.00
51	Nuvista Energy Ltd	CAN	10	292.87	NuVista Energy	1183.54	Montney AB	13617.77	8.69
52	Obsidian Energy Ltd	CAN	10	331.80	Obsidian Energy	1042.20	Peace River	929.24	58.72
52							Cardium	4333.18	11.46
53	Occidental Petroleum Corp	USA	10	17601.30	Occidental Petroleum	33756.12	Anadarko	34366.04	0.02
53							Powder River	5944.23	7.00
53							Berkine Basin – (DZA)	5793.49	59.38
53							Permian TX	216085.20	7.12
53							Mukhaizna – (OMN)	3693.24	100.00
53							Permian NM	88652.74	4.33
53							Denver Julesburg	29708.35	23.40
53							Uinta	11524.30	0.31
54	Ovintiv Inc	CAN	10	3392.28	Ovintiv	11609.74	Bakken-US	42372.34	1.91
54							Montney BC – (CAN)	19637.35	20.59
54							Permian TX	216085.20	2.03
54							Uinta	11524.30	5.50
54							Anadarko	34366.04	5.06
55	Par Pacific Holdings Inc	USA	10	871.00	PAR Pacific Holdings	1557.54	PAR Hawaii Refining LLC	1127.78	100.00
55							US Oil & Refining Co Tacoma	265.05	100.00
55							Hermes Consolidated LLC	164.71	100.00
56	Paramount Resources Ltd	CAN	10	483.76	Paramount Resources	1604.11	Montney AB	13617.77	11.78
57	Permian Resources Corp	USA	10	914.31	Permian Resources	4770.27	Permian TX	216085.20	1.39
57							Permian NM	88652.74	1.98
58	Pioneer Natural Resources Co	USA	10	2867.86	Pioneer Natural Resources	26317.82	Permian TX	216085.20	12.18
59	Range Resources Corp	USA	10	193.45	Range Resources	11978.81	Utica	29174.46	0.04
59							Other Appalachia	11132.03	0.39
59							Marcellus	145846.30	8.17
60	Rayonier Inc	USA	60	0.52	Rayonier	23.46	Fernandina Beach Pulp Mill	23.46	100.00
61	Reliance Infrastructure Ltd	IND	55	15.61	Reliance Infrastructure	4001.20	Hazira power station (Reliance)	2255.00	47.06
61							Dahanu power station	2664.00	100.00
61							BSES Kerala power station	131.00	100.00
61							Samalkot Combined Cycle	145.00	100.00
62	Ring Energy Inc	USA	10	124.59	Ring Energy	367.19	Permian TX	216085.20	0.17
62							Permian NM	88652.74	0.01
63	Rottneros AB	SWE	15	8.94	Rottneros	116.56	Vallvik Pulp Mill	116.56	100.00
64	SM Energy Co	USA	10	454.54	SM Energy	5041.52	Permian TX	216085.20	1.46
64							Austin Chalk	7572.11	13.31
64							Eagle Ford - dry gas	7626.86	11.64
65	Serica Energy PLC	GBR	10	234.28	Serica Energy	944.14	Gannet Complex	234.32	16.45
65							Rhum	905.59	100.00
66	Shandong Nanshan Aluminium Ltd	CHN	15	1504.47	Shandong Nanshan Aluminium	6802.00	Nanshan Aluminum Donghai	6802.00	100.00
67	SilverBow Resources Inc	USA	10	380.45	SilverBow Resources	1618.62	Eagle Ford - black oil	16971.16	1.86
67							Eagle Ford - condensate	14932.12	0.68
67							Eagle Ford - volatile oil	8277.93	2.56
67							Eagle Ford - dry gas	7626.86	12.98
68	Southwestern Energy Co	USA	10	1283.00	Southwestern Energy	29155.34	Other Appalachia	11132.03	0.45
68							Utica	29174.46	6.62
68							Marcellus	145846.30	10.77
68							Haynesville	68682.19	16.70
69	VAALCO Energy Inc	USA	10	310.81	VAALCO Energy	393.90	Tchatamba – (GAB)	755.96	4.65
69							Etame – (GAB)	358.72	100.00
70	Vermilion Energy Inc	CAN	10	616.18	Vermilion Energy	923.40	Cazaux – (FRA)	29.64	100.00
70							Powder River – (USA)	5944.23	1.78
70							Bakken-CA	1627.05	14.59
70							Champotran – (FRA)	57.02	100.00
70							Corrib – (IRL)	493.38	100.00

ID	Name Refinitiv	ISO3 country	GICS sector	CO2e emissions Refinitiv (Kt)	Name Trace	CO2e emissions Trace (Kt)	Installation name Trace	CO2e emissions inst. Trace (Kt)	% of interest
71	Vital Energy Inc	USA	10	452.11	Vital Energy	3938.39	Permian TX	216085.20	1.82
72	W&T Offshore Inc	USA	10	350.93	W&T Offshore	1323.82	Gulf of Mexico Shallow Shelf	6399.59	19.94
72							East Texas	14889.11	0.32
73	Wha Utilities and Power PCL	THA	55	0.36	WHA Utilities and Power	150.51	Gulf Tasit 1 & 2 power station	168.00	25.00
73							Gulf NLL power station	134.00	25.01
73							Gulf VTP power station	168.00	25.00

Notes: 'ISO3 country' refers to the country in which the headquarter of a company is located; '% of interest' indicates the share of ownership a company holds in a given installation; 'GICS Code' refers to the specific sector that a company belongs to, as classified by the Global Industry Classification Standard (GICS): 10 is 'Energy', 15 is 'Materials', 20 is 'Industrial, 55 is 'Utilities' and 60 is 'Real Estate'.

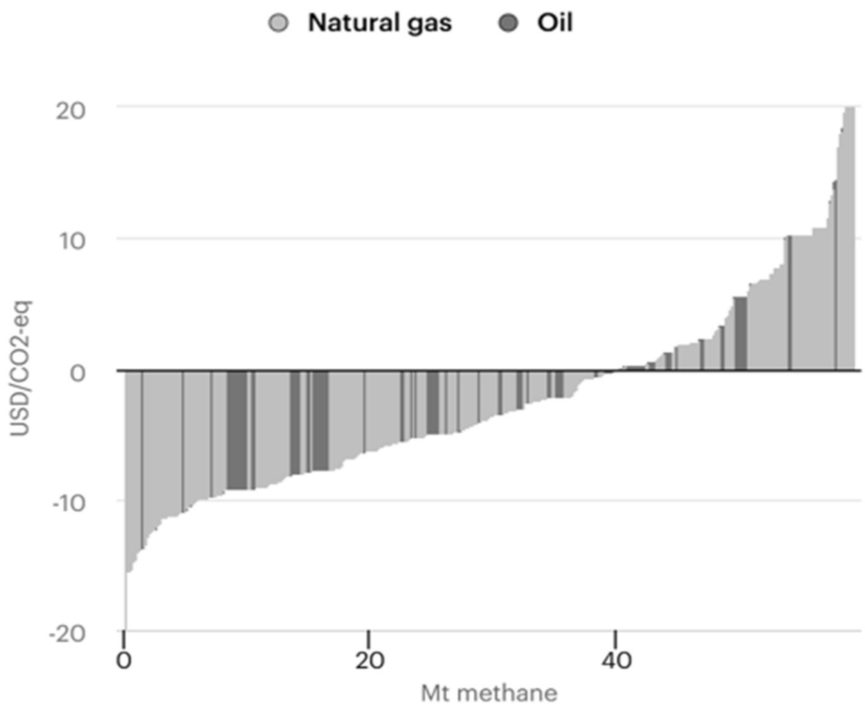
To avoid including too much information in the table above, we exclude the following airlines companies: China Eastern Airlines Corp Ltd and Greater Toronto Airports Authority. Therefore, we have 73 companies, not the 75 included in the analysis.

In the 'Installation Name Trace', if the installation is in a country different from the country where the headquarters is based, we include the installation's country in parentheses.

Annex 4. Marginal abatement cost curve for methane

UNEP (2024) estimates that approximately 50% of the 120 Mt of methane emissions from oil and gas could be avoided at no net cost, based on average energy prices in 2023. The share is lower for coal (15%) (UNEP, 2024).

Figure A4. Marginal abatement cost curve for methane from oil and natural gas operations, 2023



Source: IEA, 2024

Annex 5. Incremental labour costs of improved GHG reporting

Table A5. Estimated mean costs and revenues for facility and parent entities

Metric	Estimated values (95% confidence interval)
Mean cost to parent entity per facility (thousands) [a]	$43.1 ($42.8–$43.3)
Mean number of facilities owned per parent	4.6
Mean cost to parent for all associated facilities (thousands) [a]	$201.8 ($196.1–$207.5)
Mean parent entity revenue (billions) [a]	$11.70 ($10.90–$12.50)
Total revenue for all subpart W parents (trillions)	$8.82 ($8.22–$9.42)
Mean CRR for parent entities, using all facility costs [b]	1.05% (1.00–1.10%)

[a] Average across all existing and new reporters.
[b] Because parent revenues are heavily skewed towards higher revenues, the ratio of mean cost to mean revenue (which is approximately 0.0004%) differs substantially from the mean cost-to-revenue ratio (which is approximately 1.05%).

Source: EPA, 2024.

References

Aikman, D., Dong, Y., Drellias, E., Havaldar, S., Lepere, M., & Nilsson, M. (2023). Emissions gaming? A gap in the GHG Protocol may be facilitating gaming in accounting of GHG emissions. King's Business School. KBS Research Impact Papers, No. 1.

Alvarez, R. A., Zavala-Araiza, D., Lyon, D. R., Allen, D. T., Barkley, Z. R., Brandt, A. R., Mar, A. J. (2018). Assessment of methane emissions from the U.S. oil and gas supply chain. Science, 361, 186–188.

Badawi, A. and Bartlett, R. (2024) 'ESG Overperformance? Assessing the Use of ESG Targets in Executive Compensation Plans', *ECGI Working Paper Series in Finance*, Working Paper N° 1025/2024.

Bell, C., et al. Performance of Continuous Emission Monitoring Solutions under a Single-Blind Controlled Testing Protocol. Environ. Sci. Technol. 2023, 57, 14, 5794–5805. Published March 28, 2023. https://doi.org/10.1021/acs.est.2c09235.

Bergamaschi, P., Danila, A., Weiss, R. F., Ciais, P., Thompson, R. L., Brunner, D., . . . Houweling, S. (2018). Atmospheric monitoring and inverse modelling for verification of greenhouse gas inventories. European Commission Joint Research Centre.

Brandt, A. et al., (2022) 'Oil Production Greenhouse Gas Emissions Estimator (OPGEE) v3.0a'. California: Stanford University.

'California launches first-in-the-nation satellite project to reduce methane leaks' (2025) *California State Portal* [Preprint]. Available at: https://ww2.arb.ca.gov/news/california-launches-first-nation-satellite-project-reduce-methane-leaks.

Carattini, S., E. Hertwich, G. Melkadze, and J. G. Shrader (2022). Mandatory disclosure is key to address climate risks. Science, 378 (6618), 352–354.

Cenci, S. and Biffis, E. (2025) 'Lack of harmonisation of greenhouse gases reporting standards and the methane emissions gap', *Nature Communications*, 16(1). doi:10.1038/s41467-025-56845-3.

Chan, E., Worthy, D. E., Chan, D., Ishizawa, M., Moran, M. D., Delcloo, A., & Vogel, F. (2020). Eight-Year Estimates of Methane Emissions from Oil and Gas Operations in Western Canada Are Nearly Twice Those Reported in Inventories. Environ. Sci. Technol., 54, 14899−14909.

Chien, T., Chu, H., Hsu, W., Tseng, T., Hsu, C., & Chen, K. (2012). A Feasibility Study on the Predictive Emission Monitoring System Applied to the Hsinta Power Plant of Taiwan Power Company. Journal of the Air & Waste Management Association, 53, 1022-1028.

Conrad, B.M., Tyner, D.R. & Johnson, M.R. Robust probabilities of detection and quantification uncertainty for aerial methane detection: Examples for three airborne technologies. Remote Sensing of Environment, Vol. 288, p. 113499, available at https://doi.org/10.1016/j.rse.2023.113499. 2023

Crisp, D., Atlas, R., Breon, F.-M., Brown, L., Burrows, J., Ciais, P., . . . Ta. (2004). The Orbiting Carbon Observatory (OCO) mission. Advances in Space Research, 34(4), 700-709.

Dasgupta, S., Lall, S., & Wheeler, D. (2021). Urban CO2 Emissions a Global Analysis with New Satellite Data. World Bank Policy Research Working Paper, 9845.

Deng, Z., Ciais, P., Tzompa-Sosa, Z. A., Saunois, M., Qiu, C., Tan, C., . . . Xu, X. (2022). Comparing national greenhouse gas budgets reported in UNFCCC inventories against atmospheric inversions. Earth Syst. Sci. Data, 14, 1639–1675.

Ehlers, T., Mojon, B. and Packer, F. (2020) September 2020, Green bonds and carbon emissions: exploring the case for a rating system at the firm level. September 2020. rep. Basel: BIS.

European Union. (2018). Commission Implementing Regulation (EU) 2018/2066 of 19 December 2018, Article 21. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R2066

Fan, Y., Thomas, W. B., & Zhang, L. (2024). Customer Influence and Carbon Emissions Underreporting. SSRN.

Forster, P. *et al.* (2022) *Guest post: What the tiny remaining 1.5C carbon budget means for climate policy*, *Carbon Brief*. Available at: https://www.carbonbrief.org/.

Fouret, F. et al. (2024) Scope for improvement. Solving the Scope 3 conundrum. rep. London: FTSE Russell.

Flerlage, H., Velders, G. J., & Boer, J. d. (2021). A review of bottom-up and top-down emission estimates of hydrofluorocarbons (HFCs) in different parts of the world. Chemosphere, 283.

Fung, P. L., Al-Jaghbeer, O., Pirjola, L., Aaltonen, H., & Järvi, L. (2023). Exploring the discrepancy between top-down and bottom-up approaches of fine spatio-temporal vehicular CO2 emission in an urban road network. Science of The Total Environment, 901.

Gans, L. *et al.* (2022) 'Climate Trace: Asset & Company-Level Ownership Methodology'.

Gao, M., H. Leung, and B. Qiu (2021). Organization capital and executive performance incentives. Journal of Banking & Finance 123, 106017.

German, R., Matthews, B., & Ruyssenaars, P. (2021). Inverse modelling as a tool to support national greenhouse gas monitoring in Europe. European Topic Centre on Climate change mitigation and energy.

Gore, A. (2022). Measure emissions to manage emissions. SCIENCE, 378(6619), 455.

Gözlügöl, A.A. and Ringe, W.-G. (2022) 'Private companies: The missing link on the path to net zero', *Journal of Corporate Law Studies*, 22(2), pp. 887–929. doi:10.1080/14735970.2023.2191779.

IEA (2023) Emissions from Oil and Gas Operations in Net Zero Transitions. rep. Paris: INTERNATIONAL ENERGY AGENCY (IEA).

Ilhan, E., P. Krueger, Z. Sautner, and L. T. Starks (2023). Climate risk disclosure and institutional investors. The Review of Financial Studies, 36 (7), 2617–2650.

International Monetary Fund. (2019). Fiscal monitor: How to Mitigate Climate Change.

'IOSCO endorses the ISSB's Sustainability-related Financial Disclosures Standards' (2023). Available at: www.iosco.org/news/pdf/IOSCONEWS703.pdf (Accessed: 2023).

IPCC. (2019). IPCC 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 6.

Jervis, D., McKeever, J., Durak, B. O., Sloan, J. J., Gains, D., Varon, D. J., . . . Tarrant, E. (2021). The GHGSat-D imaging spectrometer. Atmos. Meas. Tech., 14(3), 2127-2140.

Jia, J., Ranger, N., & Chaudhury, A. (2022), 'Designing for Comparability in GHG Emissions Accounting', SSRN 4258460.

Jiang, X., Kim, S. and Lu, S. (2025) 'Limited accountability and awareness of corporate emissions target outcomes', *Nature Climate Change*, 15(3), pp. 279–286. doi:10.1038/s41558-024-02236-3.

Jing, L. *et al.* (2020) 'Carbon intensity of global crude oil refining and mitigation potential', *Nature Climate Change*, 10(6), pp. 526–532. doi:10.1038/s41558-020-0775-3.

Johnson, M. R., Tyner, D. R., Conley, S., Schwietzke, S., & Zavala-Araiza, D. (2017). Comparisons of Airborne Measurements and Inventory Estimates of Methane Emissions in the Alberta Upstream Oil and Gas Sector. Environmental Science & Technology, 51(21), 13008–13017.

Kaplan, R. and Ramanna, K. (2021), 'Accounting for Climate Change', Harvard Business Review [Preprint].

Katz, D. and L. McIntosh (2021). Corporate governance update: "materiality" in America and Abroad. In Harvard Law School Forum on Corporate Governance: Cambridge, MA, USA.

Knight, A.-L. *et al.* (2025) *Methane. A ticking time bomb for Australia's oil & gas and coal mining sectors*. rep.

LeBlanc, R. (2024) *Turning the tide: Upstream Permian methane emissions drop 26% in 2023*. rep. NYC, N.Y., S&P Global, pp. 1–8.

Lee, A.H. (2021), Living in a Material World: Myths and Misconceptions about 'Materiality', SEC.gov. Available at: https://www.sec.gov/news/speech/lee-living-material-world-052421 (Accessed: 18 January 2022).

Lepere, M., (2024) Contaminated Data? In: Carlin, D., Aikman, D., Lepere., M. and Taschini, L., ed., Accelerating Transition: Climate finance policies to prioritise in the first 100 days. London: King's Business School.

Ligori, M., Bradbury, L., Spina, R., Zee, R. E., & Germain, S. (2019). GHGSat Constellation: The Future of Monitoring Greenhouse Gas Emissions. Small Satellite Conference.

McCormick, M. (2024) 'Methane pollution at US's biggest oilfield plunges after Biden crackdown', *Financial Times*.

Nisbet, E., & Weiss, R. (2010) Top-Down Versus Bottom-Up: Can national emissions inventories be verified through direct atmospheric measurements? Science, 4, 1241-1243.

'Refinitiv Eikon - Methodology' (2020).

Rutherford, J.S., Sherwin, E.D., Ravikumar, A.P., Heath, G.A., Englander, J., Cooley, D., Lyon, D., Omara, M., Langfitt, Q., Brandt, A.R. (2021) Closing the methane gap in US oil and natural gas production emissions inventories. Nat Commun 12, 4715.

Setzer J and Higham C (2024) *Global Trends in Climate Change Litigation: 2024 Snapshot.* London: Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science.

Sherwin, E. D., Rutherford, J. S., Zhang, Z., Chen, Y., Wetherley, E. B., Yakovlev, P. V., . . . Brandt, A. R. (2024). US oil and gas system emissions from nearly one million aerial site measurements. Nature, 627, 328-334.

Shields, L. (2023) Greenhouse gas emissions reduction targets and market-based policies. Available at: https://www.ncsl.org/energy/greenhouse-gas-emissions-reduction-targets-and-market-based-policies (Accessed: 28 October 2024).

S&P. (2024) September – where does the world stand on ISSB adoption? (no date) S&P Global Homepage. Available at: https://www.spglobal.com/esg/insights/september-2024-where-does-the-world-stand-on-issb-adoption (Accessed: 06 November 2024).

Sobanaa, M., Prathiviraj, R., Selvin, J. et al. A comprehensive review on methane's dual role: effects in climate change and potential as a carbon–neutral energy source. Environ Sci Pollut Res 31, 10379–10394 (2024). https://doi.org/10.1007/s11356-023-30601-w

Thorpe, A. K., Green, R. O., Thompson, D. R., Brodrick, P. G., Chapman, J. W., Elder, C. D., D. (2023). Attribution of individual methane and carbon dioxide emission sources using EMIT observations from space. Science Advances, 9(46).

UNFCCC (2011), Materiality standard under the clean development mechanism, Framework Convention on Climate Change. Available at: https://unfccc.int/resource/docs/2011/tp/04.pdf (Accessed: 01 June 2023).

Use of auctioning revenues generated under the EU emissions trading system (no date) European Environment Agency's home page. Available at: https://www.eea.europa.eu/en/analysis/indicators/use-of-auctioning-revenues-generated#:~:text=Under%20the%20EU%20Emissions%20Trading%20System%20%28EU%20ETS%29%2C,billion%20in%202017%20to%20EUR30%20billion%20in%202022. (Accessed: 04 November 2024).

Vaughn, T. L., Bell, C. S., Pickering, C. K., Schwietzke, S., Heath, G. A., Pétron, G., . . . Nummedal, D. (2018). Temporal variability largely explains top-down/bottomup difference in methane emission estimates from a natural gas production region. PNAS, 115(46), 11712–11717.

Veefkind, J., Aben, I., McMullan, K., Förster, H., Vries, J. d., Otter, G., . . . Vink, R. (2012). TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications. Remote Sensing of Environment, 120, 70-83.

World Bank Group. (n.d.). State and Trends of Carbon Pricing Dashboard. https://carbonpricingdashboard.worldbank.org/

WRI & WBCSD. (2004). The Greenhouse Gas Protocol a Corporate Accounting and Reporting Standard. World Resources Institute & World Business Council for Sustainable Development.

WRI & WBCSD (2011), Product Life Cycle Accounting and Reporting Standard, World Resources Institute & World Business Council for Sustainable Development. Available at: https://ghgprotocol.org/sites/default/files/standards/Product-Life-Cycle-AccountingReporting-Standard_041613.pdf (Accessed: 01 June 2023).

Wu, D., Lin, J. C., Oda, T., & Kort, E. A. (2020). Space-based quantification of per capita CO_2 emissions from cities. Environ. Res. Lett., 15.

Wunch, D., Toon, G. C., Blavier, J.-F. L., Washenfelder, R. A., Notholt, J., Connor, B. J., . . . Wennberg, P. O. (2011). The Total Carbon Column Observing Network. Phil. Trans. R. Soc. A, 368, 2087-2112.

Yu, J. *et al.* (2022) 'Methane emissions from natural gas gathering pipelines in the Permian Basin', *Environmental Science & Technology Letters*, 9(11), pp. 969–974. doi:10.1021/acs.estlett.2c00380.