Fossil Fuel Operations Sector: Refining Emissions

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1. Introduction

The petroleum resources that are extracted and transformed into usable products for today's economy are not equal. In reality, their characteristics, production methods, operational stewardship - and thus, their climate impacts - vary widely (Gordon et al., 2022). By treating oil products as homogeneous, we miss opportunities to reduce greenhouse gas (GHG) emissions from the sector. Taken together, emissions from production, refining, and transportation of oil and gas represent more than 15 percent of global anthropogenic emissions. Oil refining alone represents more than three percent of global anthropogenic emissions (Gordon, et al., 2022). Therefore, these are critical sectors to mitigate to limit global temperature rise below 1.5 degrees Celsius.

The Climate TRACE oil refining sector emissions estimates rely on the methodology established by the Oil Climate Index + Gas (OCI+) tool. The OCI+ tool is built on three underlying models that estimate emissions from the oil and gas supply chain: (1) the Oil Production Greenhouse Gas Emissions Estimator (OPGEE) (Brandt, et al., 2021) assesses the upstream (production and some transport) portions of the petroleum lifecycle, (2) the Petroleum Refinery Life Cycle Emissions Model (PRELIM) assesses emissions from midstream oil refining, and (3) the Oil Products Emissions Model (OPEM) quantifies downstream end-use transport and consumption emissions from oil and gas products. More information on the OCI+ tool can be found here at https://ociplus.rmi.org/. The OPGEE model is explained in the methodology document "*Oil and Gas Production and Transport*" in the Climate TRACE GitHub methodology repository, the PRELIM model is explained further below, and OPEM is not used for emissions estimates from TRACE oil and gas sectors, since end-use is encompassed by other TRACE sectors, such as transportation and building sectors. Through the use of novel analyses of refining ground truth data to generate inputs for PRELIM. Climate TRACE provides critical insight into global sources of GHG emissions from the oil and gas sector.

2 Materials and Methods: PRELIM - Oil Refining Emissions

2.1 Source Definition

Refineries. Refineries are major industrial sites responsible for turning crude oil and gas pumped out of the Earth into the major fuels and feedstocks that underpin transportation (including gasoline, diesel, and jet fuel), heating/cooling, and everyday products. In our emissions estimates, transportation of crude oil to the refinery, and transportation of products to their end-use locations, were excluded.

Emission estimates for this sector are scope 1 of the refining process within plant gate boundaries using crude oil. This assumes all hydrogen needs are generated on-site, no power is generated on-site, and no intermediate feedstocks are exchanged between refineries. A high-level flow chart of our estimation process is displayed in Figure 1 below. More detailed information on emission estimate methodology can be found in the following sections.

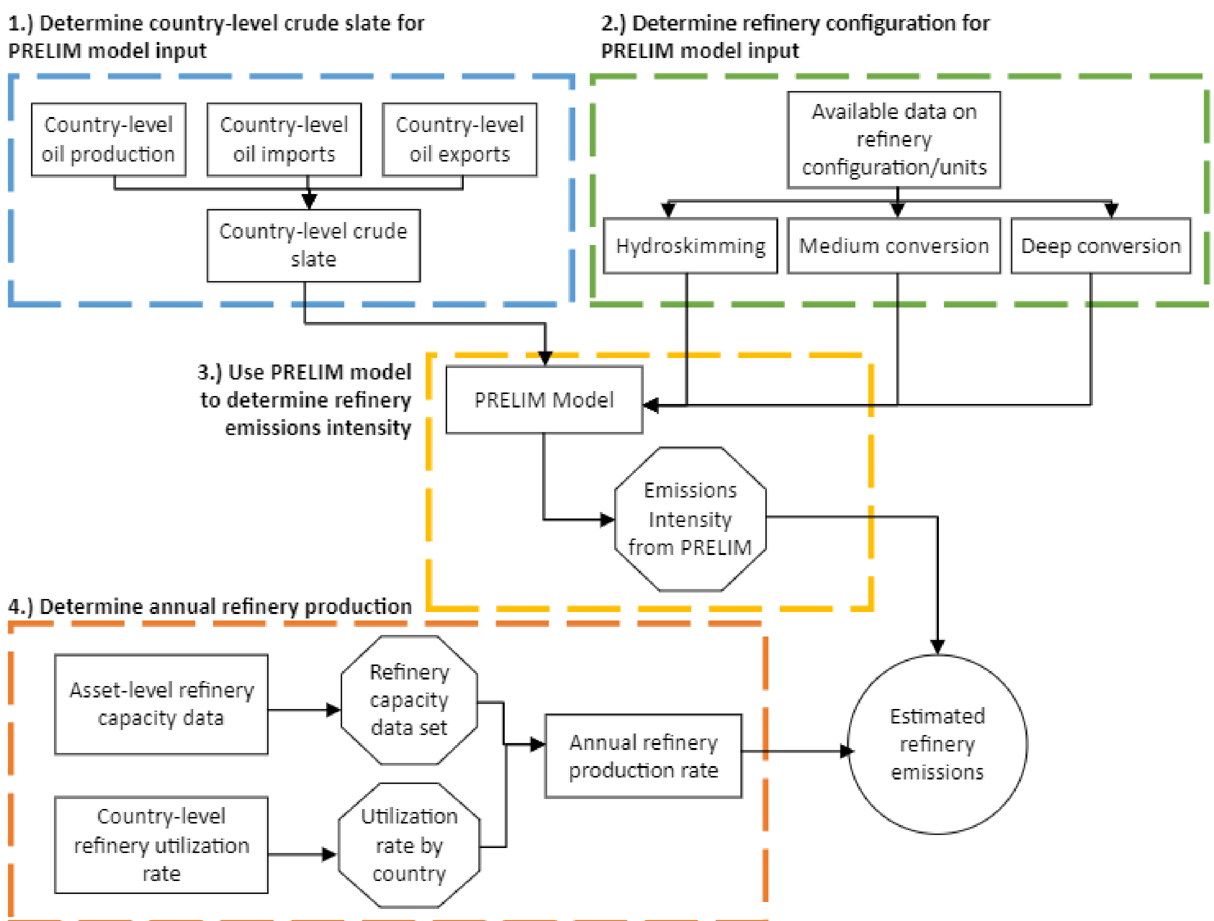

Figure 1. Refinery emission estimate methodology flowchart.

2.2 PRELIM model

RMI used the PRELIM model (v1.6) to generate refinery-level emissions estimates using refinery type-specific intensities and estimated throughputs.

PRELIM is a crude refining process model that provides emissions estimates and product slates volumes from a refinery per barrel of crude. PRELIM was developed by a team from the University of Calgary (Jing et al., 2020). The model covers fugitive and direct combustion emissions derived from unit processes refining a variety of crude oils within a range of configurations in a refinery; depending on the settings used, it can also include indirect emissions embodied in consumed electricity and upstream natural gas fugitive emissions generated off-site.

2.2.1 Emission Sources

We estimate carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and carbon dioxide equivalent (CO_2e) emissions from sources across refinery facilities, including the following main categories:

- Heat
- Steam
- Hydrogen via SMR and CNR
- FCC Catalyst Regeneration
- Flaring excess of RFG
- Subprocess Emissions
- Support Services Emissions
- Releases from Managed Wastes

2.2.2 Non-GHG Gases

In addition to CO_2, CH_4, N_2O, and CO_2e, PRELIM also assesses particulate matter and other localized pollutants. While localized pollutants were not the main focus of this analysis, these estimates were included for a few key pollutants due to their health concerns, particularly for their impact on disadvantaged populations living near oil refineries. Acidification Potential is an estimate of the compounds which are a precursor to acid rain, expressed in sulfur dioxide equivalence (SO_2eq). Particulate Matter Formation Potential, reported as PM2.5 equivalence, is an estimate of fine particles released during combustion that can be harmful to nearby populations. We also include three estimates using units called Comparative Toxic Units (CTU) which attempt to quantify localized harms per kg of emissions. For human health impacts, this localized harm is defined as disease cases per kg of emissions, covering both cancer and non-cancer illnesses; while for ecotoxicity, the estimate stands for the potentially affected fraction of species integrated over time and volume per kg of emissions (Fantke, et al., 2017).

2.2.3 Key Inputs

To estimate total emissions from the refining process, PRELIM required some key inputs to establish the parameters of the model. Prior research has demonstrated emissions results to be sensitive to these inputs (California Air Resources Board (CARB), 2021). Key inputs include:

- **Crude Assays**. PRELIM includes an assay library of over 600 crude oils from around the world. Assays contain information about the specific chemical properties of each oil, including details on API gravity (American Petroleum Institute index to measure the density of crude oil and refined products, lighter crude has higher API gravity), sulfur, nitrogen and hydrogen content, volume/mass flow (% recovery), Micro-carbon residue or

Conradson carbon residue, and Viscosity (cST at 100 °C) for vacuum residuum. These chemical characteristics influence the processes, energy, and climate impact required to turn each different source of crude into useful products. Representative assays for each refinery are selected based on each facility's configuration and location, described in more detail below.

- **Refinery Configuration.** Refineries around the world are configured to process a mix of crude oil and produce a mix of products. These configurations are defined by different combinations of process units, which turn crude oil and its derivatives into useful products. Different configurations are required depending on the type of crude being processed, and the desired mix of end products for the consuming region. Configuration has a very large impact on emissions. Generally speaking, a more complex refinery has more units, and is designed to create a wide range of end products using a heavier mix of crude oil. These more complex refineries are more emissions-intensive as a result. On the other hand, simpler refineries have fewer units and process lighter crude, resulting in a less emissions-intensive climate footprint.

PRELIM provided emissions intensities per barrel based on these and other inputs, and those per barrel figures were multiplied by our throughput estimates (explained below) to achieve annual emissions estimates for each refinery in our coverage. Climate TRACE refinery emissions modeling does not identify individual barrel supply chains from field to specific refinery. Rather, it provided an estimate of the likely refinery complexity and associated emissions based on the properties of an estimated crude oil input mix.

2.3 Datasets

Many publicly reported, technical, and academic sources served as ground truth and activity data for PRELIM. Data availability on refinery throughput, capacity, configurations and locations varies significantly by geography, so our approach varies for non-U.S. refineries and U.S. refineries. See sections below on uncertainty and confidence for more details on data quality and model accuracy. Table 2 summarizes key input data sources for PRELIM.

Table 2 Ground truth data employed as inputs to the PRELIM model.

PRELIM Model Inputs for Oil Refining		
Input	**Source**	**Regions**
Country-level utilization rate (used when more granular utilization data is unavailable)	Energy Institute Statistical Review of World Energy 2024	Global
Acquire information on U.S. refinery capacities, utilizations, configurations, and locations	U.S. Energy Information Agency (EIA): Refinery Capacity Report, and U.S. Energy Atlas	USA
Acquire information on non-U.S. refinery capacities, utilization rates, configurations, and locations	A large number of company websites, government websites, news articles, and press releases. Global Energy Observatory (GEO).	Global
Acquire information on country-level oil production, exports, and imports	Joint Organizations Data Initiative (JODI)	Global
Acquire information on country of origin for oil imports	The Observatory of Economic Complexity (OEC)	Global

2.4 Method

Refineries around the world are built in different configurations, designed to intake a certain type of crude oil, and produce a certain mix of gasoline, diesel, and other products (with limited flexibility in both inputs and outputs). The PRELIM model can be used to estimate emissions per barrel of oil refined, using information about how a refinery is configured and what type of crude oil it processes. Emissions per barrel values can then be multiplied by annual throughput to estimate annual emissions. We follow these general steps for each refinery in our dataset, estimating CO_2, CH_4, N_2O, and CO_2e emissions globally, as well as the localized pollutants described above.

2.4.1 2024 Oil Refining Release Updates

Our 2024 Climate TRACE database has been enhanced significantly by validating facility-level annual capacity and integrating more sub-national utilization from 2015 to 2023. The 2022 and 2023 releases did not include the yearly asset capacity validation. We also added 46 refineries that were missed before or were commissioned/restarted in 2023; and permanently deleted 23 refineries that had ceased operation without any sign of restart since 2015 or were double counted previously. Additionally, the 2024 release slightly adjusted the estimation approach for country-specific imported crude emission factors to align with the global average emission factors and the specific types of crude the country imports. Capacity checking and imported crude emission factor calculation amendments did not significantly affect overall global emissions versus the 2023 TRACE released results. Nevertheless, they impacted country-specific emissions considerably and differently. For instance, in some Western European countries like Germany and France, our upgraded model recorded a 14-17% reduction in CO_2e emissions, while for Spain, there was a 45% increase in CO_2e emissions. This additional information helped shed light on the transforming dynamics and trends of the refining sector through the past decade. Additionally, we redefined the capacity factor from utilization rate to effective days operating in a period. This change could better serve upcoming Climate TRACE monthly metadata updates and help standardize activity (refining throughput) calculation formulas across different sectors.

Lastly, we added one more column in the asset data profiles, "model number". This model number naming process follows the Semantic Versioning approach that is in the format of X.Y.Z (Major.Minor.Patch), where

- X stands for a major version. When the PRELIM model is upgraded, we will increase the major version number and reset both minor and patch versions to zero.
- Y stands for a minor version. When we make major methodology changes based on the same version of the PRELIM model, we will increase the minor version and reset the patch version to zero.
- Z stands for a patch version. For any small methodology changes and bug fixes, we will increase the patch version and keep both major and minor versions.

2.4.2 General PRELIM Settings

PRELIM allows users to control with many settings, but it can also choose smart defaults based on the primary inputs of crude assays and configurations. These settings include different options for many refining processes: naphtha catalytic reforming, FCC hydrotreaters, SMR hydrogen reforming, and many more. PRELIM defaults were set for these inputs, as data availability globally was challenged for these details. Additionally, asphalt production was excluded for all refineries due to limited data availability. Lastly, offsite electricity and upstream natural gas releases were excluded, which are outside the scope of the refining segments and are covered by TRACE Oil and Gas Production and Transport.

2.4.3 Non-U.S. Refineries Methodology

To find information on configurations for non-U.S. refineries, company websites, government websites, and news stories were searched, ultimately assigning each refinery to one of three PRELIM configuration categories: hydroskimming, medium conversion, or deep conversion.

Refineries in each configuration category generally have similar types of equipment, designed to process similar types of crude oil (EIA, 2012). However, configurations can vary within these categories, which is a potential source of error in our modeling. Hydroskimming refineries generally process light crude, medium conversion refineries generally process medium crude, and deep conversion refineries generally process heavy crude. This configuration information was used to provide inputs to Eq.1 to estimate emissions:

Emissions Intensity from PRELIM - The crude slate for each country was generated, which approximated the type of oil processed by refineries within each country. This began with comparing the relative size of a country's production, exports, and imports. If a country produced crude oil, it generally consumed some of the oil domestically, and perhaps exported the remainder. Imports were generally used to fill a gap between domestically available crude and crude demand. We then used PRELIM to analyze the emissions intensities of the different sources of oil based on its country of origin and weighted them proportionately to estimate refinery emissions. Sources of oil around the world have a wide range of associated emissions (Gordon, et al., 2022) and modeling the origins of a refinery's likely crude intake helps to model emissions more accurately.

A hypothetical example is provided to understand how oil domestically and imports can impact emissions estimates. Consider a medium conversion refinery in country *A*. Country *A* produces 100 thousand barrels per day (kbd), and exports 20 kbd, leaving 80 kbd of domestically available crude for processing at local refineries. Country *A* imports a total of 60 kbd of foreign crude: 40 kbd from country *B*, and 20 kbd from country *C*. So, refineries in country *A* have 80 + 60 = 140 kbd available to process each day. The theoretical mix of oil available to be processed in country *A* is ~57% domestic (80/140), ~29% from country *B* (40/140), and ~14% from country *C* (20/140). Since we are considering a medium conversion refinery that generally processes medium crudes, then the average emissions intensities of medium crude sources in countries *A*, *B*, and *C*, and weight those intensities based on their share of the country's total refinery runs. In this example, assume the average PRELIM-calculated emissions intensities of medium crudes produced in countries *A*, *B*, and *C* are 28, 30, and 32 kg CO_2/barrel of crude oil (bbl), respectively. Then country *A* medium conversion refinery's emissions intensity is calculated as: (.57*28) + (.29*30) + (.14*32) = 29.14 kg CO_2/bbl. In the case when top exporting countries do not supply the specific type of crude to the imported country, we instead used the global average emissions intensity of this type of crude

Capacity factor (effective days operating in a period) - The throughput for each facility was estimated. In opaque countries, lacking publicly available information, country-level average utilization rates were used from the Energy Institute Statistical Review of World Energy for each facility. In some countries, facility-level, regional, or other sub-national utilization statistics were identified. This information was often found on government or company websites, then more granular data for the relevant facilities were employed when available. To highlight, we specified Chinese independent refineries' (teapots) utilization rate from the country-level data because this group's operation pattern varies significantly compared to other major refineries in China. All utilization rates were then transformed to capacity factor by multiplying the number of days in the whole period to reflect effective days operating in the period.

Capacity - Facility-level capacity data source varies considerably around the world. Some governments and large oil refiners reported capacity by facility on an annual basis. However, in some countries, publicly available data was limited to news articles and the press. For some refineries in countries with limited data availability it can be challenging to find any legitimate and up-to-date sources. We have applied year-specific capacity data for all of the largest refining countries, covering approximately 75% of overall refinery coverage in our database. For the rest of the facilities, we continued to use 2022 capacity to estimate all years' throughputs, and we will continue validating the capacity accuracy for those facilities for use in future updates.

All together produces the required data needed to estimate emissions based on country-specific crude, and facility throughput in a country and capacity in Eq.1:

Emissions $\text{Estimate}_{\text{yr}}$ = Capacity *x* Capacity factor *x* Emissions Intensity from PRELIM *(Eq.1)*

2.4.4 U.S. Refineries Methodology

U.S. refineries followed the same approach described in section 2.4.3, but increased data availability allows for more granularity to define eight configuration categories (EIA, 2024). These categories include hydroskimming as noted above, as well as more detailed sub-categories of the medium conversion - fluid catalytic cracking (FCC), hydrocracking (HC), or both - and deep conversion categories (coking & FCC, coking & HC, coking & FCC & HC, coking & FCC & Residue HC). For crude slate, we first categorized what type of crude is typically run by each refinery based on the unit's present (e.g., Medium Sour), and next, computed the production-weighted average API gravity and sulfur content covering all categorized slate crudes and selected the closest representative assay from the PRELIM library based on API gravity and sulfur content characteristics (e.g., "Arab Light Solomon 2015"). Each configuration and crude assay combination was entered into PRELIM to estimate emissions intensity for each refinery. To calculate throughput, we used refinery-level capacity, combined with PADD (Petroleum Administration Defense District: government-defined subnational geographic regions in the US) and sub-PADD utilization data, both provided by the EIA. The throughput was then multiplied by emissions intensities to generate annual emissions estimates for each refinery modeled per year as done in Eq.1.

2.4.5 Confidence Categories

Confidence categories (very low, low, medium, high, very high) were assigned to our estimates to give the user a sense of the quality and consistency of the data. These categories were applied at the country level. We begin with Transparency International's Corruption Perception Index, which serves as a proxy for data availability and transparency within each country. Index values were modified by subtracting up to 20 points based on the amount of sub-national utilization data found by our team to create an Oil-Adjusted Corruption Perception Index. For example, if our estimates included sub-national utilization estimates for 50% of capacity, we would subtract 10 points from the Corruption Perception Index. We adjust downward as the oil sector is generally more opaque than other sectors. Confidence categories are defined in Table 3.

Table 3 Confidence categories assigned to oil refining data.

	Confidence Category				
	Very Low	Low	Medium	High	Very High
Oil-Adjusted Corruption Perception Index	0-19	20-39	40-59	60-79	80-100

2.4.6 Uncertainty Analysis

Our quantification of uncertainty is aimed to give the user a measure of the variation in emissions estimates derived from the PRELIM model. Uncertainty figures were calculated and applied at the configuration level.

PRELIM used distributions on several parameters to calculate emissions, and therefore there was some variation in estimates for a given set of inputs. To quantify this variation, the same inputs were run through the model 30 times for each configuration. Then the standard deviation of this range of estimates was calculated and extended the per-barrel result to annual data based on facility-level throughput. The result was the standard deviation of annual emissions estimates, based on the configuration of each facility.

2.4.7 Country-level estimation

Source-level emissions for each country were summed to obtain country-level emissions estimates. With the efforts on asset validation, we have improved global refining capacity coverage to greater than 99%, and, furthermore, improved country-level estimates for all years from 2015 - 2023 are reflected in this year's results.

3. Results

Figure 2 shows the top 10 global refining emitters for all years analyzed, 2015 to 2023. As in the Climate TRACE oil and gas production and transport sector, the U.S. shows up again as a high emitting country in the refining sector, more than double the third highest emitter (India) for most years. China's recent increase in capacity and emissions is also a significant trend, which could bring it to exceed the U.S. as the top refining emitter in the future. To highlight, China's refining capacity was slightly higher than the U.S. in 2023, given the Energy Institute's statistics. Meanwhile, the Middle East, Southeast Asia, India, and Africa can also witness an emerging refining market and, consequently, more emissions. On the contrary, many developed countries, like Japan and Germany, are steadily shrinking their refining capacity and emissions.

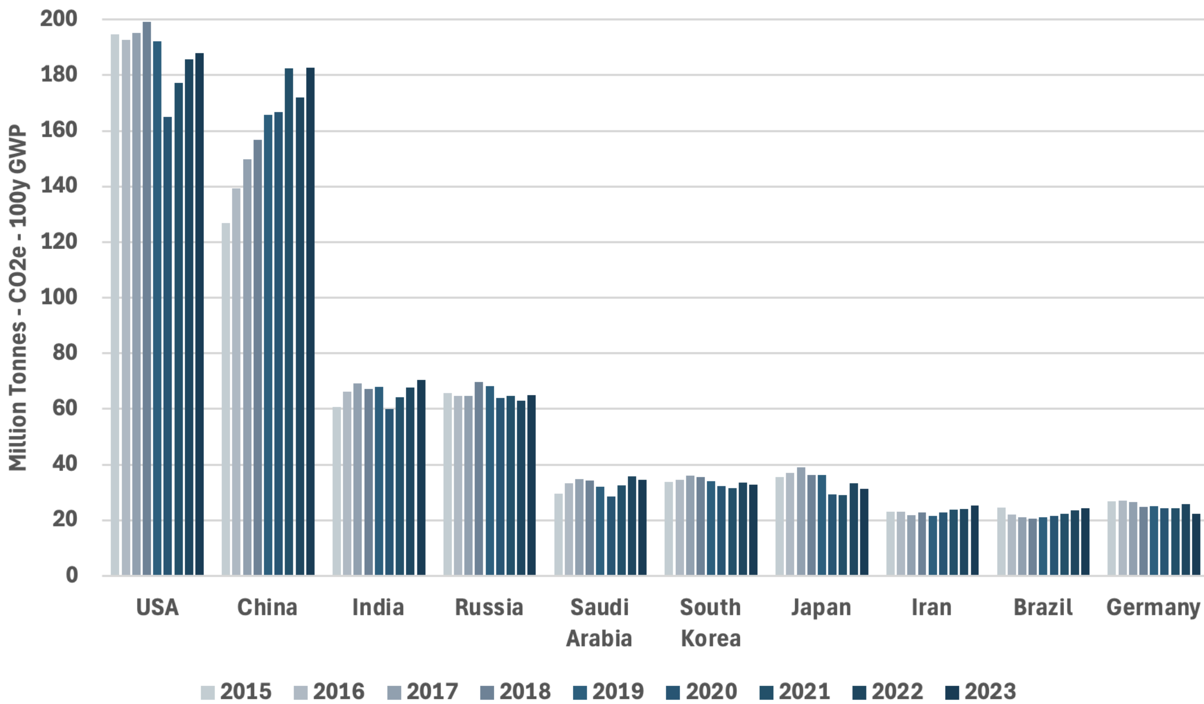

Figure 2 Top 10 global oil refining emitters, 2015-2023. Ordered by 2023 emissions.

3.1 Comparison with Other Emissions Inventories

In the refining sector, unlike the United Nations Framework Convention on Climate Change (UNFCCC) and The Emissions Database for Global Atmospheric Research (EDGAR), which generally apportion total fuel use to each sector and multiply by emission factors, PRELIM uses a systems-level approach and refinery linear programming modeling methods. This approach includes details for particular crude intake and refinery configurations down to the sub-process level and uses publicly available information whenever possible. While emission factors are used for some emissions sources, generally speaking, PRELIM modeling is far more complex and flexible than traditional emissions factor approaches. The model allows for flexibility in crude slate (the type of crude processed), configuration (which units are present and used to produce a certain mix of products like gasoline), and many other inputs. A large, public database of crude assays, and flexibility in configuration settings allows users to emulate a refinery based on those key characteristics.

Academic literature around refinery emissions has historically focused on local pollutants due to well-documented air quality concerns. The oil and gas production sector outlined in a separate methodology document is currently further along regarding remote sensing studies of key climate pollutants like methane. This is partly motivated by the fact that most methane super-emitter events detected so far have been in the production sector, while equipment further downstream is generally more consolidated and well-maintained (Alvarez, et al., 2018). While upstream has been the focus so far, remote sensing emissions studies, regarding methane in particular, are beginning to cover the refining sector as well. A recent study analyzed a sample of U.S. refineries using aircraft detections, which suggested that refinery methane emissions were ~7.5 times higher than reported inventories (Lavoie, et al., 2017). Additionally, it is likely that emissions (especially CO_2, but also CH_4) from offsite hydrogen production are underestimated in national inventories, as they can be omitted or end up in other reporting categories. Our estimation approach differs considerably from traditional emissions factor approaches, incorporating significantly more detail, and resulting in significantly different estimates as shown in Figure 3, which compares Climate TRACE oil and gas refining estimates to other emission inventories.

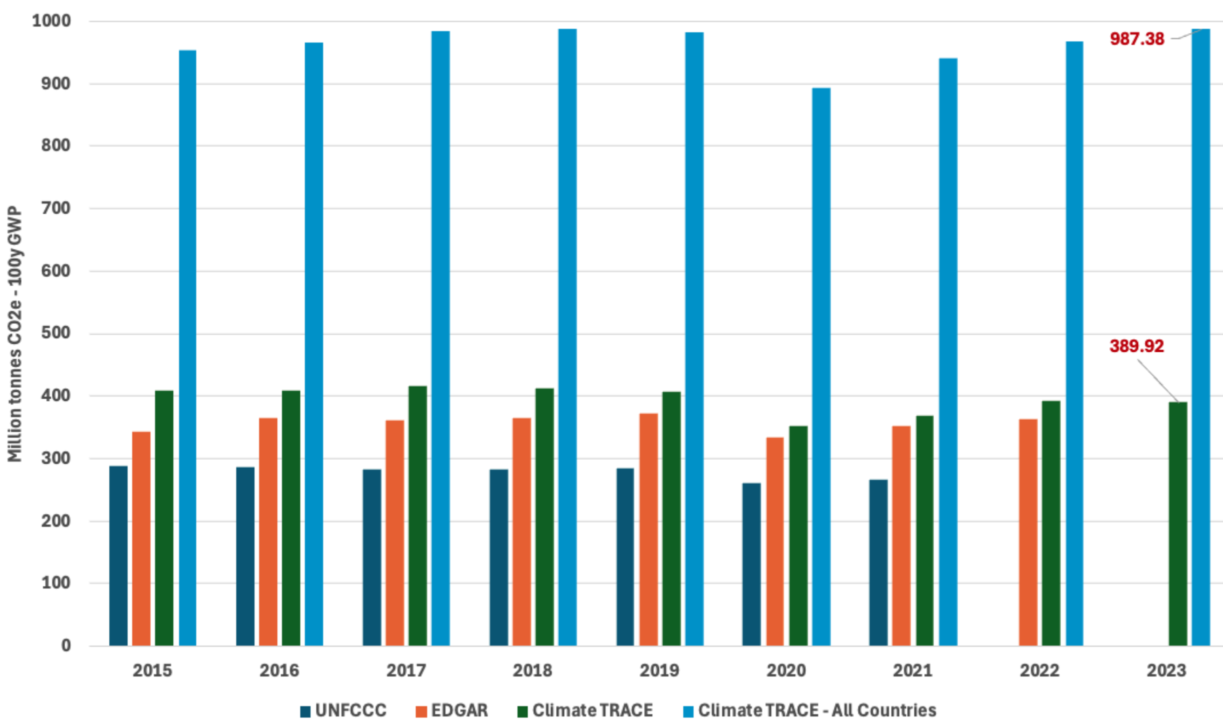

Figure 3 Comparison of global million tCO_2e (100-year GWP) estimates in the refining sector amongst most annex 1 countries. UNFCCC (dark blue bars), EDGAR (orange bars), and Climate TRACE – comparable Annex 1 subset (green bars), and Climate TRACE – All Countries (light blue bars) inventories are shown for the years 2015 to 2023. Some Annex 1 countries with highly uncertain or irregular data, such as Russia, were not included in the first three data aggregations for a more accurate comparison.

The large differences between other inventories compared to Climate TRACE in Figure 3 could be attributed to the combination of CH_4 leaks and likely missing or undercounted CO_2 emissions due to reporting issues. Because methane is weighted according to its higher GHG potential, when CH_4 is underestimated, so will CO_2 equivalent emissions.

4. Discussion

The methods and results presented here summarize emissions from the refining sector. We show that these oil and gas processing activities contribute significant amounts of greenhouse gas emissions each year. Our approach emphasizes that processing different types of crude oil using different equipment can markedly affect the amount of emissions per barrel of oil equivalent produced.

The use of the PRELIM models enables transparent, granular source emissions data. This level of granularity is not achievable globally by the other approaches. The models deployed by Climate TRACE have the capability to offer breakouts of process- and source-level emissions and to indicate which supply chain segments contribute the most emissions. With this knowledge, TRACE data can serve as a source of comparison and/or help fill knowledge gaps in existing top-down approaches. Over time, the PRELIM models via the OCI+ will also enable the differentiation of oil and gas resources for market- and policy-relevant applications. This type of transparency will ultimately be needed to make climate-informed decisions around oil and gas sources and to decarbonize the sector.

Importantly, our approach to model oil and gas emissions with OPGEE (upstream) and PRELIM (refining) also demonstrates the ability to improve and incorporate new emissions knowledge as it becomes available. For example, between the first and third iteration of the Climate TRACE inventory, we adopted higher quality and more granular model inputs, boosted comprehensiveness in country emissions scaling, and incorporated country-level crude mix estimates.

5. Limitations

Many of the limitations around our estimates stem from the lack of detailed input data. As mentioned above, data availability was very limited in some countries. Because of this problem, there is uncertainty in what mix of crude was processed by each refinery and whether there are events that would considerably impact the operation. Therefore, default assumptions in the PRELIM model were applied across most of these sites (see more details in 2.4.2 General PRELIM Settings). Specifically, we assumed refinery product slates and secondary unit capacity ratios matched PRELIM model defaults for a specified configuration, no combined heat and power systems were used, all net hydrogen needs were met through on-site SMR units, no bio-feedstocks were used, and no carbon capture units were applied for all refineries. Though the last three limitations are inherent to the latest version of the PRELIM model, we hope to address other limitations in future estimates as resources allow. Additionally, we only have sub-national utilization rates for a portion of our coverage. Operators often do not have the incentive to share this data, but basic disclosure requirements from regulators around refinery activity and emissions would result in a better understanding of emissions for those impacted locally and globally.

6. Conclusion

To chart a clean energy transition, we must bring transparency to emission-intensive sectors like oil and gas. For the refining sector, the Climate TRACE platform bolsters accountability that is currently lacking when countries self-report their emissions and offers all countries access to reliable, accurate, and timely emissions data across sectors. The information can empower leaders to pinpoint where efforts should be channeled to maximize impact.

More information and techniques will be applied to improve and refine our oil and gas sector emission estimates. For the PRELIM refining model, we will pursue data necessary to level up from refinery category intensities towards sub-national and refinery-specific estimates with our partners at University of Calgary (e.g., individual refinery configurations, crude oil assay pairings, temporally granular throughput data).

Since empirical measurements cannot be made over all facilities, in all geographies, all the time, this will require improving our models' capabilities to make smarter assumptions in data-poor environments. This includes the integration of current and emerging remote sensing technologies that have the capabilities to assess GHGs from oil and gas systems. No singular remote sensing system can overcome all the hurdles to capturing the majority of GHG emission sources, but combining different technologies can work towards high resolution measurements, with credible verification and transparency, at scale. A promising future of emissions monitoring lies in a layered system that integrates a suite of measurement technologies, models, and reported data.

Acknowledgements

Special thanks to our partners at Climate TRACE, Development Seed, Carbon Mapper, Stanford University, the University of Calgary, NASA - Carbon Monitoring System, Colorado School of Mines, and Harvard University that helped with developing the models we deployed, building web tools to share results with public audiences, constructing this document, and working with us to integrate other approaches to and knowledge of oil and gas emissions into these estimates.

Supplemental Section Metadata

Dataset Description:

This sector's dataset includes emissions estimates for oil refinery facilities globally. Estimates were made at the facility level using the PRELIM model and a range of data inputs which vary based on availability, but generally include an approximation of the type of crude oil processed, the facility's capacity, and its annual utilization rate. Coverage was considered to be more than 99% of global refinery capacity, so facility-level emissions estimates are summed to produce country-level estimates.

Table S1 General dataset information for Oil Refining Segment**.**

General Description	Definition
Sector definition	*Global Refineries*
UNFCCC sector equivalent	*1.A.1.b Petroleum Refining*
Temporal Coverage	*2015 – 2023*
Temporal Resolution	*Annual*
Data format(s)	*CSV*
Coordinate Reference System	*EPSG:4326, decimal degrees*
Number of sources available for download and percent of global emissions (as of 2023)	*707 sources representing approximately 99% or more of this sector's emissions.*
Total emissions for 2023	*Approximately 987.4 million tonnes CO_2e*
Ownership	*Obtained from government and company websites, as well as news stories*
What emission factors were used?	*Many process-level emissions factors are used in the PRELIM model – see PRELIM documentation and model for a complete list.*
What is the difference between a "NULL / none / nan" versus "0" data field?	*"0" values are for true non-existent emissions. If we know that the sector has emissions for that specific gas, but the gas was not modeled, this is represented by "NULL/none/nan"*
total_CO2e_100yrGWP and total_CO2e_20yrGWP conversions	*Climate TRACE uses IPCC AR6 CO_2e GWPs. CO_2e conversion guidelines are here:* https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FullReport_small.pdf

Table S2 Source level metadata description confidence and uncertainty for petrochemicals. See Table 3 for Confidence categories assigned to oil refining data.

Data Attribute	Confidence Definition	Uncertainty Definition
type	*country level confidence in configuration data*	*N/A*
capacity_description	*country level confidence in capacity data*	*N/A*
capacity_factor_description	*country level confidence in utilization data*	*N/A*
capacity_factor_units	*N/A*	*N/A*
activity_description	*country level confidence in utilization data*	*N/A*

CO2_emissions_factor	*country level confidence in emissions factor*	*standard deviation of PRELIM-generated per barrel emissions factor, based on configuration*
CH4_emissions_factor	*country level confidence in emissions factor*	*standard deviation of PRELIM-generated per barrel emissions factor, based on configuration*
N2O_emissions_factor	*country level confidence in emissions factor*	*standard deviation of PRELIM-generated per barrel emissions factor, based on configuration*
other_gas_emissions_factor	*N/A*	*N/A*
CO2_emissions	*country level confidence in emissions estimate*	*standard deviation of annual estimate, based on configuration and throughput*
CH4_emissions	*country level confidence in emissions estimate*	*standard deviation of annual estimate, based on configuration and throughput*
N2O_emissions	*country level confidence in emissions estimate*	*standard deviation of annual estimate, based on configuration and throughput*
other_gas_emissions	*N/A*	*N/A*
total_CO2e_100yrGWP	*country level confidence in emissions estimate*	*standard deviation of annual estimate, based on configuration and throughput*
total_CO2e_20yrGWP	*country level confidence in emissions estimate*	*standard deviation of annual estimate, based on configuration and throughput*

Data citation format: Wang, J., Fallurin, J., Peltier, M., Conway, T., Gordon, D. (2024). *Fossil Fuel Operations Sector- Refining Emissions.* RMI, USA, Climate TRACE Emissions Inventory. https://climatetrace.org [Accessed date]

Geographic boundaries and names (iso3_country data attribute): The depiction and use of boundaries, geographic names and related data shown on maps and included in lists, tables, documents, and databases on Climate TRACE are generated from the Global Administrative Areas (GADM) project (Version 4.1 released on 16 July 2022) along with their corresponding ISO3 codes, and with the following adaptations:

- HKG (China, Hong Kong Special Administrative Region) and MAC (China, Macao Special Administrative Region) are reported at GADM level 0 (country/national);
- Kosovo has been assigned the ISO3 code ‘XKX’;
- XCA (Caspian Sea) has been removed from GADM level 0 and the area assigned to countries based on the extent of their territorial waters;
- XAD (Akrotiri and Dhekelia), XCL (Clipperton Island), XPI (Paracel Islands) and XSP (Spratly Islands) are not included in the Climate TRACE dataset;
- ZNC name changed to ‘Turkish Republic of Northern Cyprus’ at GADM level 0;
- The borders between India, Pakistan and China have been assigned to these countries based on GADM codes Z01 to Z09.

The above usage is not warranted to be error free and does not imply the expression of any opinion whatsoever on the part of Climate TRACE Coalition and its partners concerning the legal status of any country, area or territory or of its authorities, or concerning the delimitation of its borders.

Disclaimer: The emissions provided for this sector are our current best estimates of emissions, and we are committed to continually increasing the accuracy of the models on all levels. Please review our terms of use and the sector-specific methodology documentation before using the data. If you identify an error or would like to participate in our data validation process, please contact us.

References

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