Fossil Fuel Operations sector: Petrochemical Ethylene Steam Cracker Emissions

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1. Introduction

Plastics and similar petrochemical products make up a growing share of the petroleum industry's climate impacts. Demand for organic high-value petrochemicals could drive over half of world oil demand by 2050 (IEA, 2022). The petrochemical industry is an incredibly diverse sector covering a range of assets and products. A significant portion of the sector's supply flows through ethylene steam crackers, which convert refined oil products and natural gas liquids into ethylene and similar major organic chemicals.

The petrochemical industry consists of a plethora of different processing units and ethylene steam crackers are the first step into this diverse landscape. Steam crackers represent the next processing step for refined oil and gas streams to chemicals for many products. They also produce a range of hydrocarbon intermediates that serve as material inputs for clothing, medical equipment, electrical transmission cables, solar panels, wind turbines, and electric vehicles among many other products. These assets have significant emissions impacts, generating up to half of full life-cycle emissions for many petrochemicals like polyethylene plastic packaging films (Sphera, 2022). As the world seeks to limit global temperature rise below 1.5 degrees Celsius, this sector will become increasingly important, for both the products it produces and the emissions it creates.

Currently there is no comprehensive asset and emissions inventory for these energy intensive steam cracker units. Understanding the emissions footprint of these assets provides insight into the petrochemical industry globally. These initial Climate TRACE petrochemical emission estimations currently use academically reviewed emissions factors published by the Intergovernmental Panel on Climate Change (IPCC) by region and feedstock. Applying these factors to reasonable estimates of production and feed type provides critical initial insight into global sources of petrochemical greenhouse gas emissions.

2. Materials and Methods

Figure 1 gives an overview of the method for determining steam cracker emissions. Data on steam cracker capacity was compiled and adjusted by utilization rates to represent actual production. This ethylene steam cracker production data was then multiplied by a feedstock weighted regional emission factor to provide steam cracker emission estimates. More detailed information on this methodology can be found in the following sections.

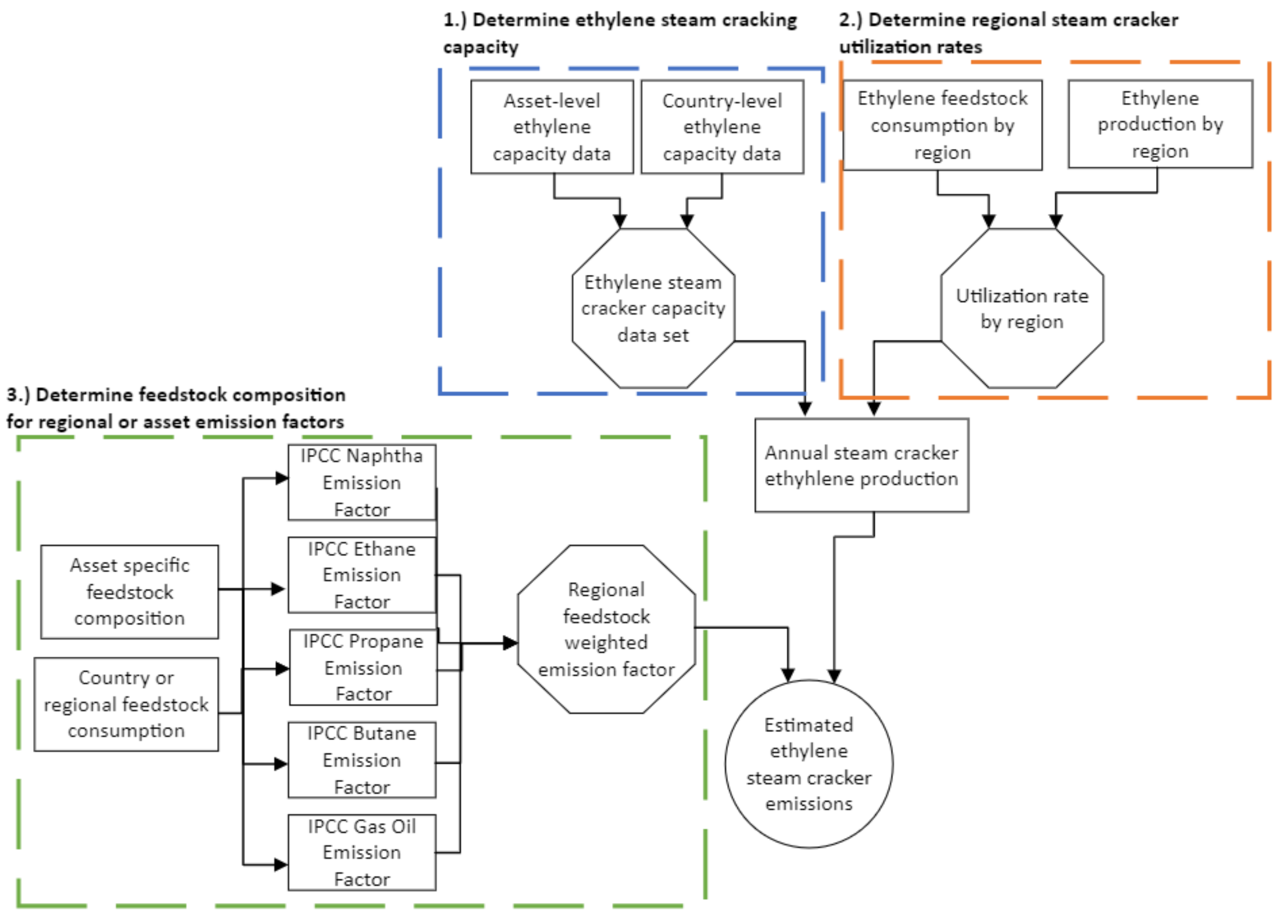

Figure 1. Steam cracker emission estimate methodology flowchart.

2.1 Asset Definition- Petrochemical Ethylene Steam Crackers

Ethylene Steam Crackers. Steam cracking is a petrochemical process that applies high temperature heat to hydrocarbon feed and steam to thermally crack hydrocarbons bigger than methane into several organic chemicals including olefins (ethylene, propylene, butylene) and sometimes aromatics (benzene, toluene, xylene). These products, known in industry as high value chemicals, then serve as feedstocks for many petrochemical products including bulk commodity plastics (HDPE, LDPE, LLDPE, PVC, PET, and PP), detergents, solvents, and other specialty chemicals. Steam crackers can be co-located with a refinery petrochemical complex or part of stand-alone chemical sites; both stand-alone and integrated steam crackers were included in our emissions estimates. Steam crackers were aggregated to the site level, where a stated facility's capacity could include one or multiple cracker units. We excluded the transport of feedstocks and products in our emissions estimates. Site-level emissions were only provided within China, Europe, and the United States. Country-level ethylene steam cracker emissions were provided for the rest of the world.

Integrated Facilities. Integrated facilities refer to sites that consist of both a refinery and steam cracker operated by the same company (or its chemical subsidiary, or joint venture) co-located in the same facility. These integrated sites will share some utility and logistical infrastructure.

2.2 Emissions Determination

2.2.1 Emissions

Climate TRACE used emissions factors for steam cracking by feed type and region from the IPCC's Emission Factor Database (IPCC, 2006). Asset and country-level emissions were determined using these emissions factors, estimated feedstock compositions, and estimated throughputs for each asset or country.

2.2.2 Gasses

Emissions were based on overall CO_2 equivalency reported at the asset or country level. Estimations for emissions of CO_2 and CH_4 were included separately for each estimated asset or country.

2.2.3 Key Inputs

Feed Type. Steam crackers use naphtha, gas oil, liquified petroleum gas (LPG), ethane, propane, or butane as feed. Steam crackers that use naphtha or gas oil, heavier range hydrocarbon feeds, are less efficient at producing ethylene and are therefore more emissions intensive. Conversely, steam crackers that use LPG or ethane for feed produce higher yields of ethylene and are less emissions intensive per ton of ethylene produced. To economically optimize assets some steam crackers are "flex steam crackers"; able to run a combination of multiple feeds. Our method assumed these sites used both naphtha and LPG/ethane feeds with different ratios. All sites integrated to refineries were assumed as "flex steam crackers" unless public sources specified otherwise.

2.3 Data Sets

Data was collected separately for asset-level estimations in the U.S., China, and Europe and country-level data for the rest of the world. Data sources primarily used for asset emissions in the U.S., China, and Europe are summarized below. All data was publicly available. Global country-level coverage is estimated at 99%. Asset coverage for the U.S. and Europe is estimated to be 100% with China coverage estimated to be 98%.

Table 1 Data sources by region.

Inputs for Steam Cracker Emissions		
Input	**Source**	**Region**
Emissions Factors	IPCC EFDB (IPCC,2006)	Global
Information on US steam cracker capacity, locations, and feed type	US Energy Information Agency (EIA, 2023), company websites, government websites, and news articles	USA
Information on Europe steam cracker capacity, locations, and feed type	Petrochemicals Europe (Petrochemicals Europe, n.d.), company websites, government websites, and news articles	Europe
Information on China steam cracker capacity, locations, and feed type	Company websites, government websites, and news articles	China
Information on country level ethylene steam cracker capacity	Company websites, government websites, trade associations, and news articles	Global

2.4 Method

Sections 2.4.1-2.4.3 cover the methodology for asset-level emissions in the U.S., Europe, and China. Section 2.4.4 covers the country-level emissions methodology for the rest of the world. Generally, Equation 1 was used to determine asset and country-level emissions with more detailed information on underlying assumptions provided in the sections below.

Emissions = Ethylene Capacity *x* Utilization *x* Regional Emissions Factor (Eq.1)

Where the Emissions in tons of CO_2, CH_4, or CO_2eq per year is a function of:

"Ethylene Capacity": the ethylene production capacity of a site, in tons of ethylene per year.

"Utilization": the ratio of annual ethylene production over ethylene capacity on a regional basis, in percent.

"Regional Emissions Factor": the IPCC emissions factor weighted by feedstock mix for country or asset,in tons of CO_2, CH_4, or CO_2eq per ton of ethylene

2.4.1 Asset Capacity Methodology

Data on the ethylene capacity of steam crackers was sourced from the data sets listed in Table 1. Where applicable, the steam cracker capacity by region was compared to aggregated asset-level data as a back check for accuracy. Data on unit start up and/or capacity additions over the last five years was compiled if applicable.

2.4.2 Asset Throughput Methodology

Throughput estimations for steam crackers were determined by multiplying asset capacity by estimated utilization, the "Ethylene Capacity" and "Utilization" in Eq.1. Where more granular data was available, regional utilization numbers were determined and applied to steam cracker capacity. For example, for the U.S., data on ethane supplied was compared to U.S. cracker capacity to develop a regional utilization (EIA, 2023). Similarly, for European crackers, data on production and capacity provided regional utilization (Petrochemicals Europe, n.d.). For China, ethylene production numbers were adjusted by a scaling factor of 120% and were used to determine utilization by year (Li et al. 2022; National Statistics Network Direct Reporting Portal, 2022). See key assumptions in Table 2 for key assumptions on utilization and feed by region. Note that for Europe, no update was provided for 2022 throughput and an average of 2018-2021 utilization was assumed for 2022.

Table 2 Key Assumptions for Asset Emissions Calculations

Utilization and Feed Mix	United States	European Union	China
Stand-alone Flex Cracker Feed Mix	Ethane	70% Naphtha, 15% Propane, 15% Butane	87% Naphtha, 7.8% Propane, 5.2% Butane
Integrated Refinery Cracker Feed Mix	70% Ethane, 10% Propane, 10% Naphtha, 10% Butane	50% Naphtha, 17% Propane, 17% Butane, 10% Ethane, 6% Gas Oil	87% Naphtha, 7.8% Propane, 5.2% Butane
Utilization Data Source	Energy Information Administration/American Chemistry Council	Petrochemicals Europe	National Bureau of Statistics and Transforming China's Chemicals Industry report

2.4.3 Asset Emissions Methodology

Individual steam crackers emissions were determined by multiplying the relevant feed emissions factors by estimated asset annual throughput, the "Regional Emissions Factor" and "Ethylene Capacity"/ "Utilization" in Eq. 1. For flex steam crackers not integrated with a refinery the feed type was assigned based on publicly available information on feedstock type. Where this information was unavailable, regional economic incentives for naphtha vs. ethane/LPG feedstock combined with available information on feedstock consumption by region was used to estimate feedstock for steam cracking assets. The stand-alone flex cracker feed for each region can be found in the key assumptions table (Table 2). For flex steam crackers integrated with a refinery, a similar regional approach for feed mix was determined. The feed mix assumption by region can be found in the key assumptions table (Table 2). This method was repeated for each individual asset. Country-level estimates for these regions were determined by summing the asset-level estimates by country. For 2023 asset data collection efforts focused on the U.S., Europe, and China which represent nearly half of ethylene steam cracker capacity.

2.4.4 Country-level Emissions Methodology (excluding the U.S., Europe, and China)

To determine ethylene capacity in the rest of the world that lacks identifiable asset level information, data was pulled from multiple publicly available sources on ethylene capacity in regions and countries for 2021. To determine ethylene throughput at a country-level, utilization rates of downstream polyethylene processing units for 2021 by region were applied as a proxy for steam cracker utilization. To determine production for years before and after 2021, year over year (YOY) growth rates for petrochemical feedstocks consumption by region were applied to a country's 2021 ethylene production (Energy Institute, 2023).

As with asset emission estimates, feedstock composition is a crucial factor in determining country-level emission estimates. If specific data at a regional or country level was found from publicly available sources, it was used to set the feedstock mix for a country. For the remaining countries, the ratio of ethane/LPG versus naphtha consumption was used as a proxy to estimate feedstock mix (Energy Institute, 2023). Regions with ratios of ethane/LPG to naphtha consumption similar to the U.S. were assumed to have a predominantly ethane/LPG feedstock mix while regions with consumption ratios similar to Europe were assumed to have a predominantly naphtha feedstock mix.

2.4.5 Confidence Categories

A confidence level was determined for each asset's data inputs. The confidence level (very low, low, medium, high, or very high) indicates the data quality and availability used to make assumptions for asset emission estimates. To determine a confidence interval, the 2022 Corruption Perception Index was used as a proxy for data quality by country (Transparency International, 2022). Our emissions estimates rely upon publicly available data from government or news sources and the Corruption Perception Index provides a score for perception of corruption in the public sector by country. This data provides a proxy for the perceived reliability and accuracy of our data sources. . The raw corruption perception index value was used for each country unless the country was a part of the Petrochemical Europe data set. In that case, the perception index value was increased by ten to represent the increased confidence in data quality. Using this method each asset was assigned a confidence level according to their adjusted corruption perception index value: 0-45 very low, 45-65 low, 65-85 medium, 85-100 high, >100 very high.

2.4.6 Uncertainty Analysis

For emission factors, the IPCC uncertainty ranges defined in Volume 3, Chapter 3, Table 3.16 in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories were applied to provide low and high uncertainty ranges. These ranges were applied to the overall asset emission estimates by multiplying the standard deviation of the emission factor by asset throughput in 2022. This method provides an uncertainty estimate for the asset emissions but does not include any numerical uncertainty in the asset capacity, utilization, or feed composition assumptions.

3. Results: Petrochemicals

Figure 2 displays the total global emissions from ethylene steam crackers for the TRACE data set. Global steam cracking emissions are estimated at 260 $MTCO_2e$/year (Sarin & Singh, 2022) to 300 $MTCO_2e$/year (Amghizar et. al,. 2020) and the current TRACE data set covers 99% of global steam cracker emissions when including country-level estimates with total steam cracking emissions estimated at 283 $MTCO_2e$/year. Global steam cracking capacity is estimated at 190 MT ethylene/year (Gelder, 2023). The current TRACE data set represents 99% of global steam cracking capacity when including country-level estimates. The TRACE asset-level data set covers 51% of global ethylene steam cracking capacity and emissions.

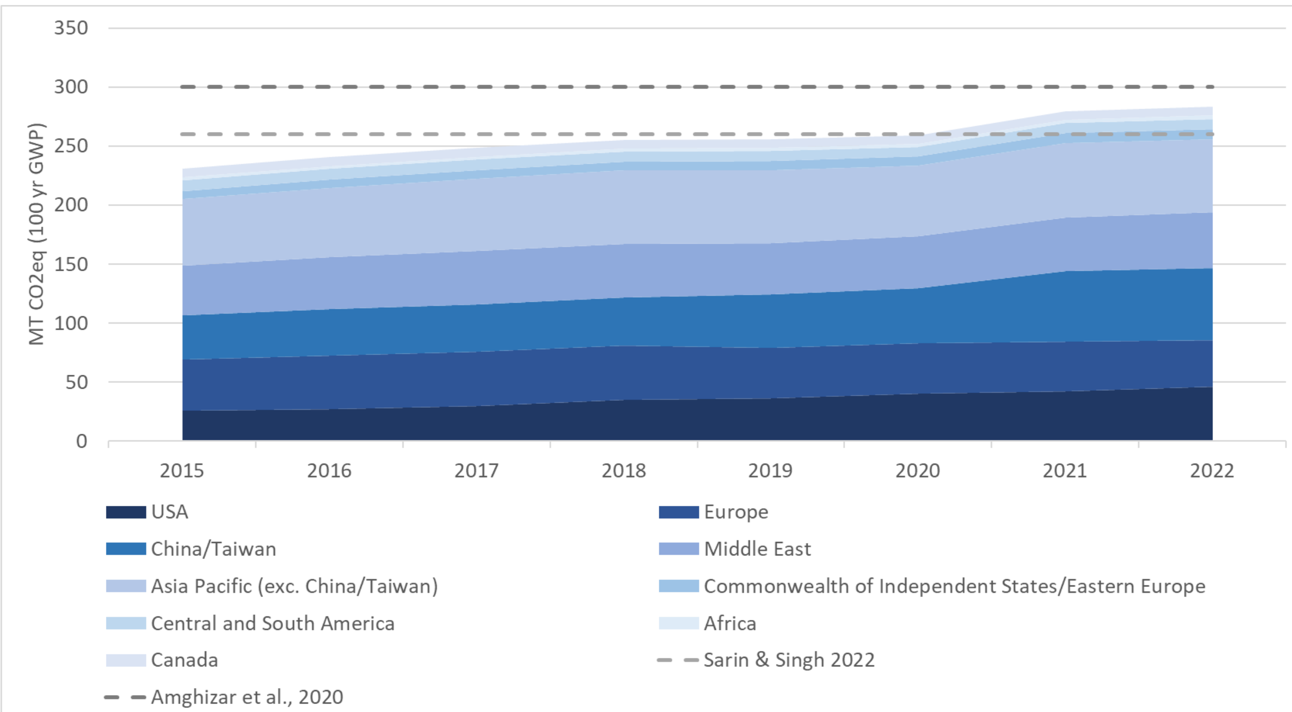

Figure 2 Climate TRACE emission estimates by region.

3.1 Comparison to Other Emission Inventories

Very few comprehensive estimates for ethylene steam cracking emissions exist; therefore, the focus of this analysis is on the asset-level estimates for Europe, the U.S., and China. Figure 3 below displays the UNFCCC 2.B.8.b Ethylene results for Annex 1 countries and Climate TRACE results for the same countries. For European UNFCCC results only countries that reported CO_2 emissions with ethylene production were included. Several countries reported no

CO_2 emissions with ethylene production, attributing those emissions to either industrial stationary combustion or other chemical processes.

There are significant differences in the UNFCCC and Climate TRACE results that vary by region. Much of this delta can be attributed to methodological differences. The UNFCCC numbers are created from national inventory reports from each country. There is no standard methodology between nations completing these inventory results, creating hard to quantify differences. For example, Switzerland, the country with the largest emissions difference to TRACE numbers, includes emissions from ammonia production along with site ethylene emissions. This results in a higher emissions number for Switzerland ethylene production in UNFCCC but does not represent actual emissions attributable to ethylene production by steam cracking; the only emissions calculated for Climate TRACE. Other European emission difference root causes were not individually reviewed for each country but are also likely largely due to similar methodological differences. As a result, Climate TRACE values for European steam crackers are lower than those in UNFCCC. The UNFCCC results for U.S. ethylene emissions are significantly lower than those determined by TRACE for all years (Figure 3).

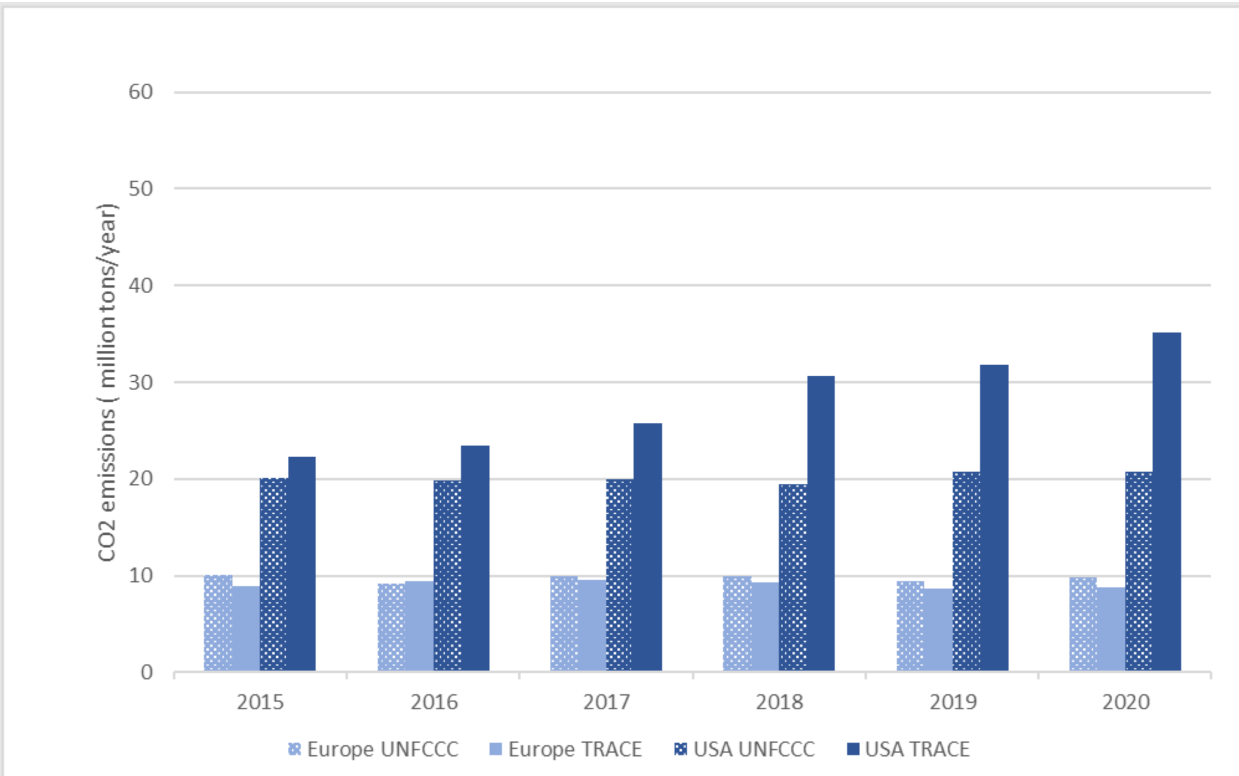

Figure 3. UNFCCC and Climate TRACE emission comparisons for U.S. and Europe for years 2015 to 2022.

In the U.S., petrochemical facilities report emissions to the Greenhouse Gas Reporting Program (GHGRP) which compiles this emissions data for the Greenhouse Gas Inventory (GHGI) which makes up the national inventory report (Environmental Protection Agency, 2023). A comparison of UNFCCC reported emissions, emissions reported to the GHGRP, and emissions calculated by TRACE are shown in Figure 4 below. Emissions reported to GHGRP are on a site level and can include emissions associated with further downstream processing beyond ethylene production likely accounting for the UNFCCC and GHGRP reported emissions discrepancy, but no explicit methodology was provided for converting site reported GHGRP emissions to UNFCCC inventories.

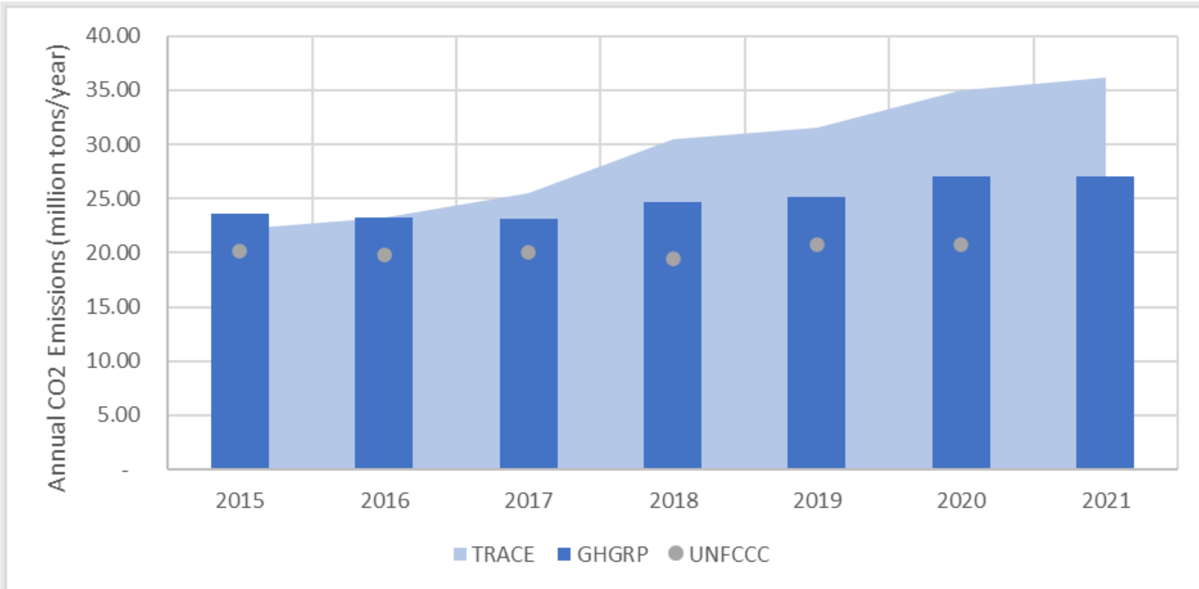

Figure 4. U.S. GHGRP, UNFCCC, and TRACE emission comparisons for years 2015 to 2021.

TRACE and UNFCCC inventories both show significant additional ethylene production from 2015-2020, in the range of 7 million tons per year increased ethylene production; however, TRACE emissions estimates show a proportional increase in associated emissions and UNFCCC/GHGRP data does not. Review of GHGRP reported emissions on a site-by-site basis identified that some sites are categorizing emissions differently than others. Specifically, some refinery integrated sites are attributing only emissions associated with petrochemical flaring to ethylene cracker reporting, while attributing remaining process heat emissions to the associated refinery. The majority of emissions from ethylene production come from process heat, steam and electricity; reporting only flaring emissions will result in significant undercounting of total process emissions attributed to ethylene production. The GHGRP emissions accounting boundary has room for interpretation which has resulted in this reporting discrepancy and the large delta between TRACE and UNFCCC ethylene emissions inventory for the U.S.

Efforts were made to correct this reporting discrepancy in the GHGRP emissions inventory. Process heat emissions that should be attributed to ethylene production were pulled from site GHGRP emission inventory reports. These emissions were then added to the flaring petrochemical emissions reported to the GHGRP as ethylene production emissions. When comparing these results to the TRACE modeled emissions, agreement between U.S. ethylene emissions inventory methods was very strong (see Figure 5 below) . Earlier discrepancies where TRACE emissions were lower than GHGRP reported emissions can likely be attributed to the feedstock slate shift from naphtha to lighter ethane/LPG in U.S. ethylene steam cracking. TRACE data likely overcounts ethane-based steam cracking versus naphtha-based steam cracking in 2015-2017 compared to the reality, resulting in lower emissions estimates than reported in those years.

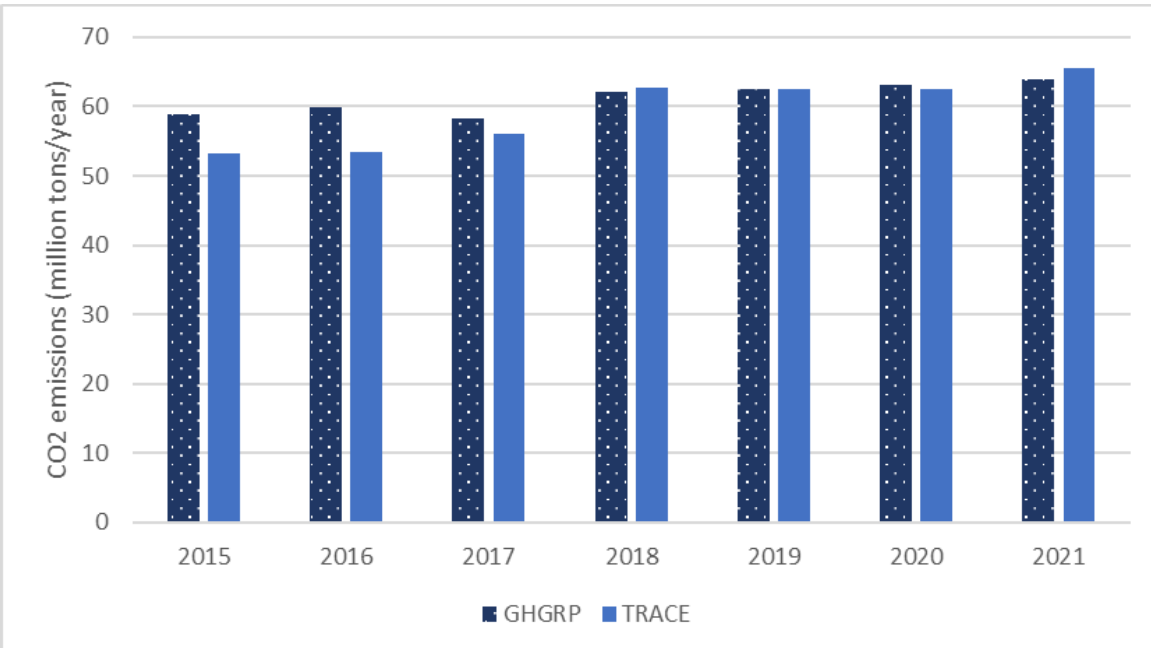

Figure 5. U.S. GHGRP adjusted and TRACE emissions comparisons for years 2015 to 2021.

Data on China ethylene emissions was limited. Only a single data point from 2020 sourced from RMI's Transforming China's Chemicals Industry report was found to compare to TRACE results. TRACE ethylene steam cracker emissions were lower than reported ethylene process emissions from China. This discrepancy is likely due to the prevalence of coal-to-olefin and methanol-to-olefin pathways in China. These ethylene production pathways would not be included in the TRACE data set which only estimates emissions from ethylene steam cracking. These pathways are emissions intensive and estimated to represent 14% of total ethylene production capacity in China.

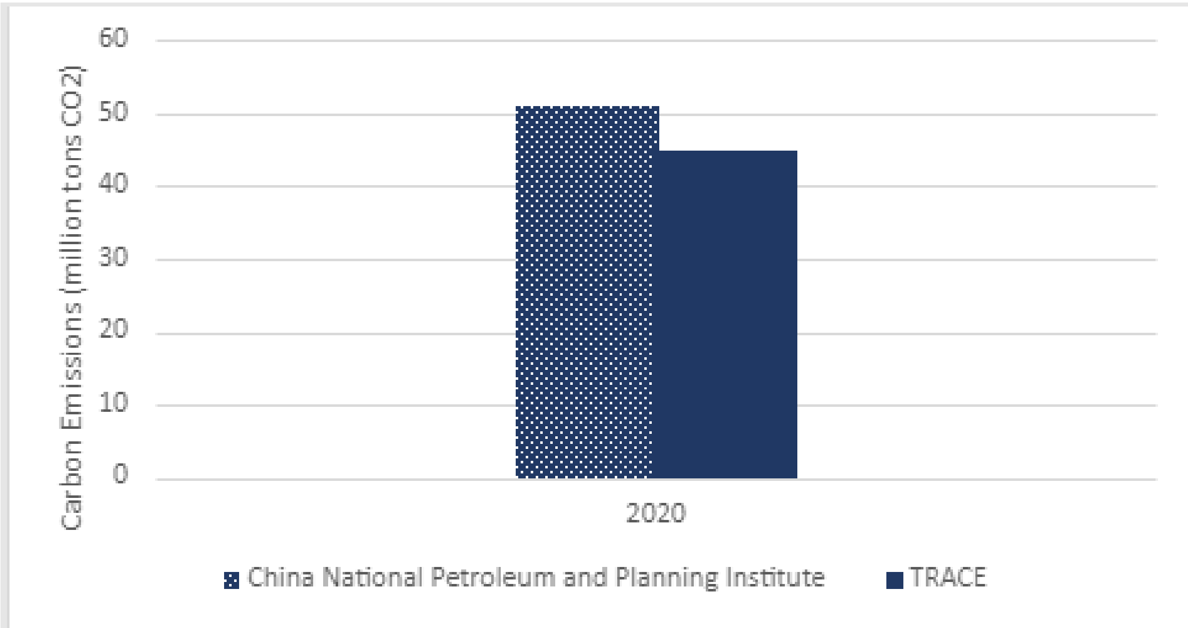

Figure 6. China National Petroleum and Planning Institute and TRACE emissions comparisons for 2020.

4. Discussion: Petrochemical Ethylene Steam Crackers

The methods and results presented here summarize emissions from ethylene steam cracking. We show that these activities contribute significant amounts of greenhouse gas emissions each year, with demonstrated increases in both capacity and emissions in several major regions. These trends are expected to continue as oil and gas companies continue to invest in downstream petrochemical applications to replace transportation fuel demand. Additional ethylene steam crackers are anticipated to start up over the next five to ten years resulting in increased emissions in the sector.

The use of the IPCC emissions factors allows for transparent emissions and country-level data for ethylene steam crackers. The IPCC factors represent a well agreed upon base level comparable to other academically reviewed papers' emissions factors and provide transparency into emissions calculations. While these emission factors represent a good starting point, more robust process modelings similar to the refinery PRELIM model for steam crackers would provide a more accurate emissions estimate. Currently PRELIM only models refinery emissions but ongoing work with the University of Calgary is looking to expand the PRELIM model into chemicals production including a more advanced ethylene steam cracker model (Bergerson, 2022). This work will be necessary to make climate informed decisions around petrochemical assets to decarbonize the sector.

Our results show reasonable agreement with some inventories while drawing attention to differences in others. Overall, there is limited information available on emissions inventories for ethylene steam cracking and methodological differences in the UNFCCC national inventory reports can create confusion on regional ethylene production carbon intensity. The Climate TRACE approach offers a novel, independent data set that applies and expands upon trusted models with roots in academia and policy.

Importantly, our approach to steam cracker emissions will have the ability to improve and incorporate new emissions knowledge as it becomes available. As models like PRELIM evolve our Climate TRACE emissions methodology will evolve as well, providing more detailed granular emissions modeling for steam cracking. As detection technology and regulation evolve in the petrochemical and related industries, we will continue to incorporate the best-in-class available information to ensure emissions estimates at the asset, sub-national, and country level keep pace.

4.1 Limitations

Current emissions estimates for ethylene steam cracking rely on an emission factor-based approach. While these emissions factors have been compared to other academic papers, they do not represent more granular emissions data for process heat, flaring, electricity, etc. at a site. Additionally, data availability and quality varies greatly by region especially when it comes to feedstock type at a site, one of the most impactful assumptions to the emissions calculation. This potentially results in emissions estimates that are too high or low for a given region. A best effort was made to collect up-to-date accurate data. Finally, while other oil and gas sector supply chain segments for Climate TRACE incorporate satellite data such as VIIRS flaring data, ethylene steam cracking does not currently include any remote sensing data.

5. Conclusion

To chart a clean energy transition, we must bring transparency to emission-intensive sectors like petrochemicals. The petrochemicals sector is difficult to trace due to complex supply chains and a vast array of products but modeling emissions from ethylene steam crackers represents a valuable first step and useful addition to the production and refining oil and gas sectors. 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. This 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 petrochemical sector emission estimates. We will continue to collaborate with our University of Calgary partners to advance the modeling efforts for steam crackers and other petrochemical assets in PRELIM. We will boost country coverage (percent of country assets modeled) to improve data granularity in regions outside of the U.S., China, and Europe, where possible, and highlight data gaps by advocating for improved data availability with stakeholders in specific geographies. Currently, no remote sensing data is included in our ethylene steam cracker emissions estimates, but we will continue to increase our understanding of data availability to incorporate these emerging technologies into emissions modeling for improved accuracy.

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 oil and gas models that underlie much of this work and are continuing to pursue advancement of the oil and gas emissions modeling work into the downstream petrochemical sector.

Supplemental section metadata

Covered Emissions and Available Data: Only ethylene steam cracking unit emissions were modeled in this data set. Any other ethylene production pathways such as coal-to-olefin or methanol-to-olefin are not included in the dataset. The asset and country-level data that is freely available on the website can be found in Tables 4, 5 and 6 below. Additional information on ethylene capacity by country for country-level emission estimates can be shared upon request.

Table S1. General dataset information for petrochemicals

General Description	Definition
Sector Definition	*Petrochemicals covering ethylene steam cracking assets*
UNFCCC sector equivalent	*2.B.8.b Ethylene*
Temporal Coverage	*2015-2022*
Temporal Resolution	*Annual*
Data format(s)	*CSV or GeoTIFF*
Coordinate Reference System	*ESPG:4326, decimal degrees*
Number of assets/countries available for download and percent of global emissions (as of 2022)	*Data covers 52 countries representing 99% of global emissions and 116 assets representing 51% of global emissions*
Total emissions for 2022	*283 million tons of CO2e*
Ownership	*We used research and news sources to identify ownership information*
What emission factors were used?	*IPCC Tier 1*
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 CO2e GWPs. CO2e conversion guidelines are here: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Full*

Table S2 Asset level metadata description for petrochemicals

Data attribute	Definition
sector	*fossil-fuel-operations*
asset_sub-sector_name	*petrochemicals*
asset_definition	*ethylene steam cracker*
start_date	*year modeled*
end_date	*year modeled*
asset_identifier	*TRACE ID number for facility*
asset_name	*common name of steam cracker facility*
iso3_country	*country code*
location	*location of facility with point inside site*
type	*feed for steam cracker*
capacity_description	*maximum ethylene production capacity*
capacity_units	*tons of ethylene per year*
capacity_factor_description	*utilization of asset*
capacity_factor_units	*percentage*
activity_description	*ethylene production*
activity_units	*tons of ethylene per year*
CO2_emissions_factor	*IPCC tier 1 emissions factor*
CH4_emissions_factor	*IPCC tier 1 emissions factor*
N2O_emissions_factor	*not modeled*
other_gas_emissions_factor	*not modeled*
CO2_emissions	*annual absolute CO2 emissions estimate*
CH4_emissions	*annual absolute CH4 emissions estimate*
N2O_emissions	*not modeled*
other_gas_emissions	*not modeled*
total_CO2e_100yrGWP	*annual CO2e emissions in 100 year global warming potential*
total_CO2e_20yrGWP	*annual CO2e emissions in 200 year global warming potential*
other1_description	*refinery TRACE ID for integrated asset*
other1_units	*N/A*

Table S3. Asset level metadata description confidence and uncertainty for petrochemicals.

Data Attribute	Confidence Definition	Uncertainty Definition
type	*country level confidence in feedstock 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*	*IPCC high and low ranges*
CH4_emissions_factor	*country level confidence in emissions factor*	*IPCC high and low ranges*
N2O_emissions_factor	*N/A*	*N/A*
other_gas_emissions_factor	*N/A*	*N/A*
CO2_emissions	*country level confidence in emissions*	*IPCC high and low ranges*
CH4_emissions	*country level confidence in emissions*	*IPCC high and low ranges*
N2O_emissions	*N/A*	*N/A*
other_gas_emissions	*N/A*	*N/A*
total_CO2e_100yrGWP	*country level confidence in emissions*	*IPCC high and low ranges*
total_CO2e_20yrGWP	*country level confidence in emissions*	*IPCC high and low ranges*

Data citation format: Peltier, M; Fallurin, J; Wang, J; Conway, TJ; and Gordon, D (2023). *Petrochemical Ethylene Steam Cracker 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.

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