Manufacturing and Industrial Processes 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 primary 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 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.

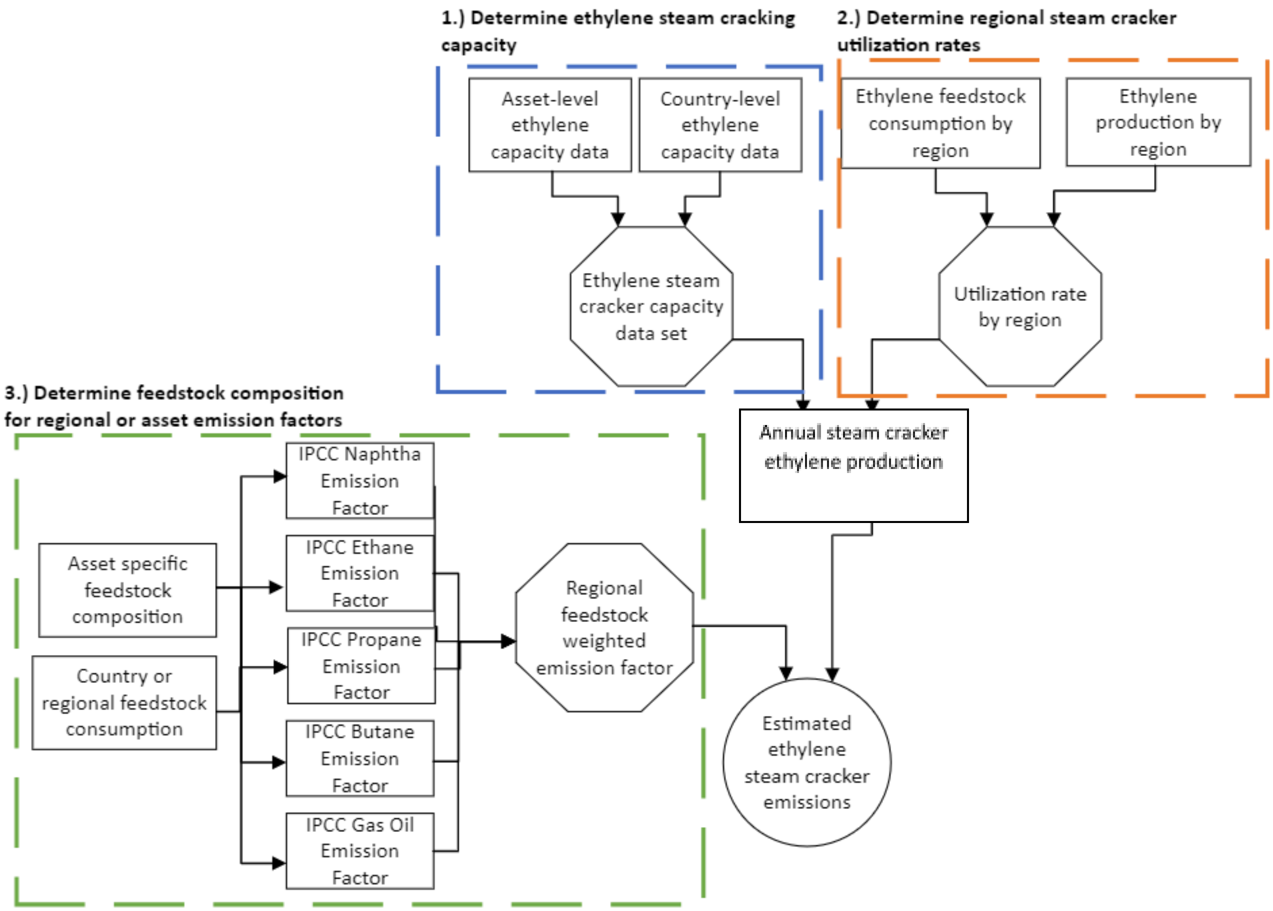

Figure 1. Steam cracker emission estimate methodology flowchart.

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 larger 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.

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. In addition to the IPCC base emissions factor, a flaring factor of 1.075 was applied to all assets based on data provided in the IPCC's Emission Factor Database supplemental information (IPCC, 2006).

2.2.2 Gasses

Emissions were based on overall CO_2 equivalency (CO_2e) reported at the asset or country level. Estimations for emissions of carbon dioxide (CO_2) and methane (CH_4) were included separately for each estimated asset or country. Additional other non-greenhouse gas emissions for the sector were provided separately, see Non-Greenhouse Gas Emissions Estimates Across Sectors methodology on the TRACE website for more details.

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 for asset-level estimations globally, with asset-level coverage estimated at 92%. Data sources were publicly available at the time of this writing and summarized in Table 1.

Table 1 Data sources by region and source.

Inputs for Steam Cracker Emissions		
Input	**Source**	**Region**
Emissions Factors	IPCC EFDB	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 Japan steam cracker capacity, locations, and feed type	Japan's Ministry of Economy, Trade, and Industry Statistics, company websites, and news articles	Japan
Information on Mexico steam cracker capacity, locations, and feed type	Pemex's website and news articles	Mexico
Information on rest of the world steam cracker capacity, locations, and feed type	Company websites, government websites, and news articles	Global

2.4 Method

Sections 2.4.1-2.4.5 cover the methodology for annual asset-level emissions globally. Country-level emissions were determined by summing asset-level emissions within each country. Equation 1 was used to determine asset-level emissions with more detailed information on the underlying assumptions provided in the sections below.

Emissions = Ethylene Capacity *x* Utilization *x* Regional Emissions Factor *x* Flaring 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

"Flaring Factor": 1.075 emission factor applied to represent flaring emissions per IPCC supplemental information for steam crackers.

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 (CEFIC, 2023). For China, nationally reported ethylene production numbers 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 some key assumptions on utilization and feed in select regions. For countries outside of these regions a similar approach was used, incorporating regionally specific data when applicable.

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 (2023)	CEFIC (2023)	National Bureau of Statistics China (2023)

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 some regions 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 for some regions can be found in the key assumptions table (Table 2). This method was repeated for each individual asset.

2.4.4 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 2023 Corruption Perception Index was used as a proxy for data quality by country (Transparency International, 2023). Our emissions estimates rely upon publicly available data from government or news sources and the Corruption Perception Index provides a score for the 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.

2.4.5 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 2023. 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 Climate TRACE data set along with other reported values. China, Asia Pacific, North America, and the Middle East are the largest emitting regions. Previous global steam cracking emissions are estimated at 260 $MTCO_2e$/year (Sarin & Singh, 2022) to 300 $MTCO_2e$/year (Amghizar et. al,. 2020) in 2022 and 2020 respectively. In contrast, Climate TRACE emissions estimates provide granular emissions estimates annually from 2015 to 2023, with 2023 steam cracker emissions estimated at 296 $MTCO_2e$, the highest of all the reported years. These yearly emissions updates are based on our monitoring of capacity change, utilization shift, and other emission-related operational issues, ideally at the facility level.

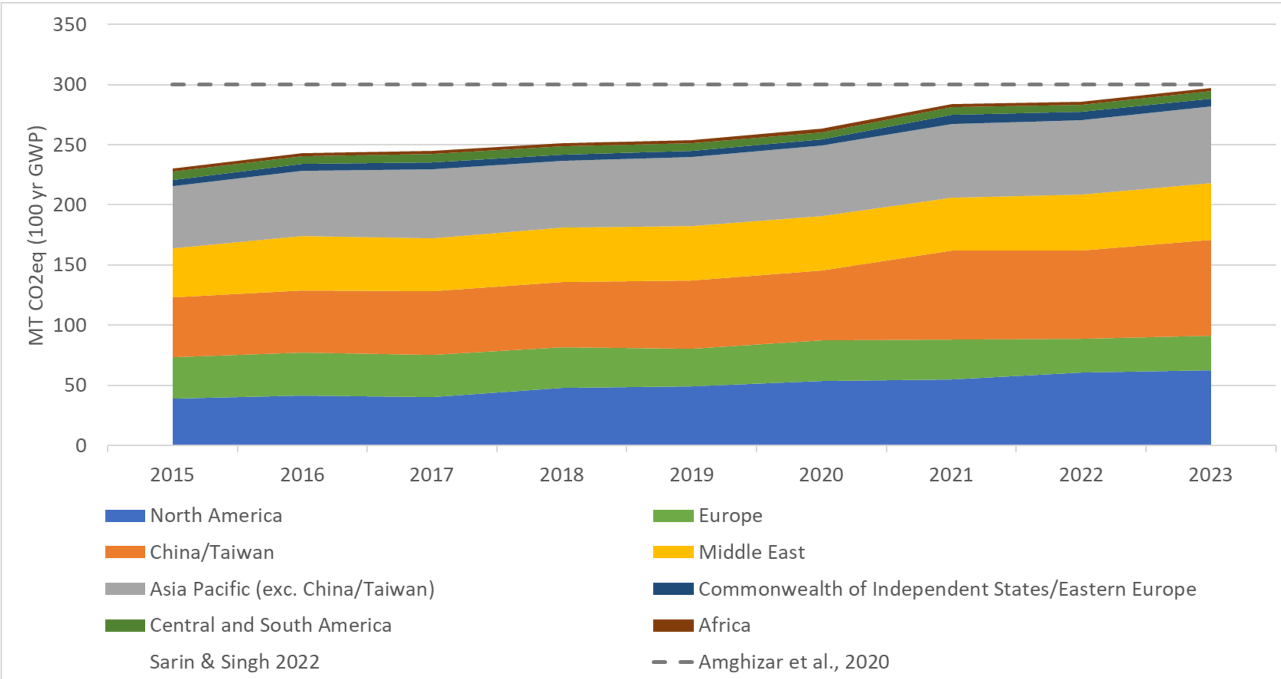

Figure 2 Climate TRACE emission estimates by region. Each region contains the following countries- North America (light blue): Canada, U.S., and Mexico; China/Taiwan (orange); Asia Pacific exc. China/Taiwan (gray): Australia, India, Indonesia, Japan, Malaysia, Philippines, Singapore, South Korea, and Thailand; Central and South America (dark green): Argentina, Brazil, Colombia, and Venezuela; Europe (light green); Austria, Bulgaria, Belgium, Croatia, Czech Republic, Finland, France, Germany, Greece, Hungary, Italy, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Spain, Sweden, Switzerland, Turkey, and United Kingdom; Middle East (yellow): Iran, Iraq, Israel, Kuwait, Oman, Qatar, Saudi Arabia, and United Arab Emirates; Commonwealth of Independent States/Eastern Europe (dark blue): Azerbaijan, Belarus, Russia, Serbia, Turkmenistan, Ukraine, and Uzbekistan; Africa (dark red): Algeria, Egypt, Libya, Nigeria, and South Africa.

Global steam cracking capacity is estimated to be 190 MT ethylene/year in 2022 (Gelder, 2023). The current TRACE asset data set represents 205 MT ethylene/year in 2022, within 15% of this 2022 asset estimate. TRACE asset capacity increased to 211 MT ethylene/yr in 2023 with an increase in emissions from the sector to 296 $MTCO_2e$. On a country level, China, the United States, and Saudi Arabia have the largest operating ethylene capacities and therefore highest emissions in this sector in 2023.

Compared to last year's 2023 Climate TRACE estimates, the 2024 total emissions estimates for the petrochemical sector are within 1%. When assets are aggregated to a global level, both year's results show similar values; however, at an individual country level differences occurred in regions that did not have asset level emissions estimates previously in 2023. For countries estimated on an asset basis last year, the results were 5-10% higher in the U.S. and China and about 10% lower in European countries. The U.S. and China's increase in estimated emissions can be attributed to slight adjustments in utilization and the increase in emissions from the flaring factor. Lower European emissions can be attributed to an adjustment in utilization rates from CEFIC that was lower than the assumed utilization in last year's, 2023, submission.

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 comparisons between Climate TRACE and United Nations Framework Convention on Climate Change (UNFCCC) reported emissions. Figure 3 below displays the UNFCCC 2.B.8.b Ethylene and Climate TRACE results for Annex 1 countries. Several countries displayed (i.e. FRA, GBR, and NLD) in Figure 3 reported no CO_2 emissions with ethylene production, attributing those emissions to either industrial stationary combustion or other chemical processes.

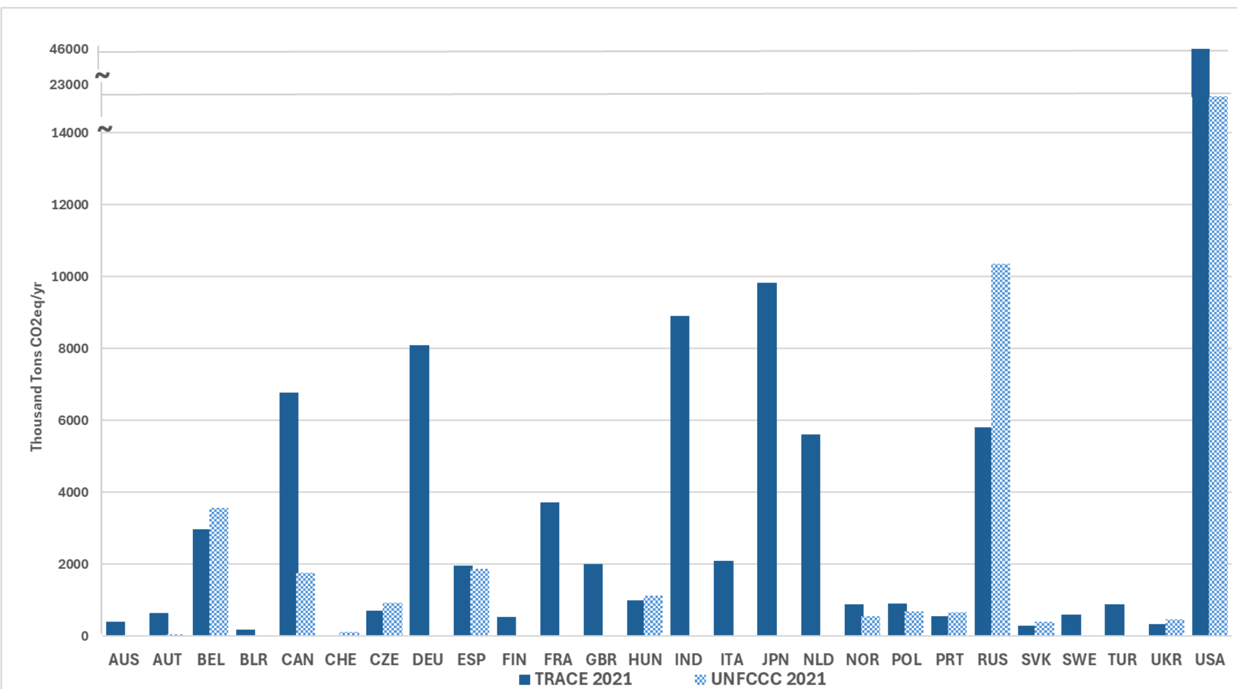

Figure 3 UNFCCC (dark blue bars) and Climate TRACE (bars with light blue dots) emission comparisons for Annex 1 countries in 2021. Only UNFCCC 2021 emissions estimates were compared being the most recent emissions data available.

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. To better understand discrepancies between each inventory, each country's national inventory reports were reviewed and the most likely reason for the discrepancies is the UNFCCC reporting guidelines. Table 3 describes each country's approach to report emissions and showcases the challenges when comparing this sector’s emissions between countries.

Table 3. Review of UNFCCC National Inventory Reports (NIRs) and comparison to Climate TRACE inventories.

UNFCCC Emissions Reporting Status	**Country**	**Comments**
UNFCCC does not report any emissions in 2.B.8.b ethylene production	AUS	NIR report specifies there are ethylene production facilities in Australia, but no info is provided on ethylene production and only emission factors for CH_4 and VOCs are provided. There is language in the NIR regarding legislation which protects companies from having to share data which might mean that all chemical production is aggregated up together in Australia's NIR submission. (Australian Government Department of Climate Change, Energy, the Environment and Water 2021)
	DEU	"The production-quantity data for methanol and ethylene dichloride are subject to confidentiality requirements in certain years. For these reasons, all production quantities for the products in groups a) through e) are aggregated and then reported, together with the pertinent CO_2 and CH_4 emissions, under 2.B.8.g "(ethylene is b in this grouping). Additionally, "related CO_2 emissions of steam cracker units, which are far and away the largest group of emitters considered in this context, occur almost exclusively via combustion in cracking furnaces, auxiliary boilers or flares. With the exception of flares in the petrochemical industry, such combustion-related emissions are included in the energy-sector section in 1.A.2.c." (Federal Environment Agency)
	FRA	"Emissions from ethylene, ethylene dichloride and propylene are estimated together and cannot be reported separately." The combined emissions from chemical production are reported under 2.8.10. (Ministère de la Transition Écologique)
	JPN	Emissions from ethylene are listed as confidential so no data is provided, results are likely aggregated up under total petrochemical production emissions. (Ministry of the Environment, Japan Greenhouse Gas Inventory Office of Japan (GIO), CGER, NIES)
	NLD	CO_2 emissions from the production of silicon carbide, carbon black, methanol and ethylene from the combustion of residual gas (a by-product of the non-energy use of fuels) are included in 1.A.2.c (Chemicals). Although these CO_2 emissions are more or less process-related, they are included in 1.A.2 to keep consistency with energy statistics that account for the combustion of residual gases. Additionally, petrochemical production emissions are aggregated up into total petrochemical production emissions. (National Institute for Public Health and the Environment)

UNFCCC Emissions Reporting Status	Country	Comments
	SWE	"Production of petrochemical products (ethylene, ethylene dichloride and vinyl chloride monomer and ethylene oxide) as well as carbon black, which are described in IPCC 2006 Guidelines under CRF 2.B.8, are included in 2.B.10 due to difficulties in separating these emissions." (Swedish Environmental Protection Agency)
	TUR	The majority of ethylene production emissions are reported in section 1.A.2. " This fuel is named "fuel gas" and emissions due to the combustion of fuel gas is included in the energy sector. However, some of the fuel gas is combusted in the flare stacks and the emissions from the flare stacks are included in the IPPU category." These remaining fuel gas emissions are aggregated up into petrochemical production. (Turkish Statistical Institute)
UNFCCC 2.B.8.b ethylene production emissions are significantly lower than Climate TRACE emissions	AUT	Energy emissions from combustion including flaring are reported under 1.A.2.c. Only methane emissions are reported under 2.B.8.b. (Federal Ministry of Climate Action, Environment, Energy, Mobility, Innovation and Technology 2022)
	CAN	Canada uses a 0.411 kg/kg CO_2 emission factor for their steam crackers which is more than 50% lower than IPCC factors. Data is based on surveys of individual sites. Process emissions are explicitly called out, likely indicating combustion emissions are accounted for elsewhere. Chemicals are included in 1.A.2 emissions. Information on the determination of the emissions factor was very difficult to find, likely a similar issue to the USA discrepancy. (Environment and Climate Change Canada 2023)
	FIN	All CO_2 emissions are reported in the Energy sector, therefore CO2 emissions from ethylene production are reported as IE. Fugitive CH4 emissions from flanges, valves, and other process equipment from ethylene production are included in the 2.B.8.b inventory. (Statistics Finland)
	GBR	Ethylene production is incorrectly listed under 2.B.8.g while methanol production emissions are reported under 2.B.8.b. (Department for Business, Energy & Industrial Strategy 2023)
	ITA	No specific language included but only CH_4 emissions are calculated for ethylene production. Likely that CO_2 emissions are either in 1.A.2 or are not accounted for. (The Institute for Environmental Protection and Research)
	IND	India only reported emissions in 2016 and there is good agreement in that year, about a 3.5% difference from TRACE results.
	USA	See section below and Figures 4 and 5 for a detailed review of the large USA discrepancy. (United States Environmental Protection Agency 2023)
UNFCCC 2.B.8.b ethylene production emissions are	RUS	Russia uses a 1.73 (IPCC's Western Europe Naphtha Cracker) emissions factor *130% correction factor for CO_2 emissions. This has been constant across reporting years. Climate TRACE takes a more asset level approach determining feed on an asset-by-asset basis. Many new crackers built in Russia are next to gas plants and are expected to use a gas-based feed contributing to lower emission results for Climate TRACE assets. (Federal

UNFCCC Emissions Reporting Status	Country	Comments
significantly higher than Climate TRACE emissions		Service for Hydrometeorology and Environmental Monitoring (Roshydromet))

A deeper dive into the U.S. UNFCCC and Climate TRACE difference is warranted as the country represents some of the largest total steam cracker emissions globally. 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. Data is only provided to 2021 as that is the most recent available UNFCCC data. 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 the GHGI and ultimately UNFCCC inventories.

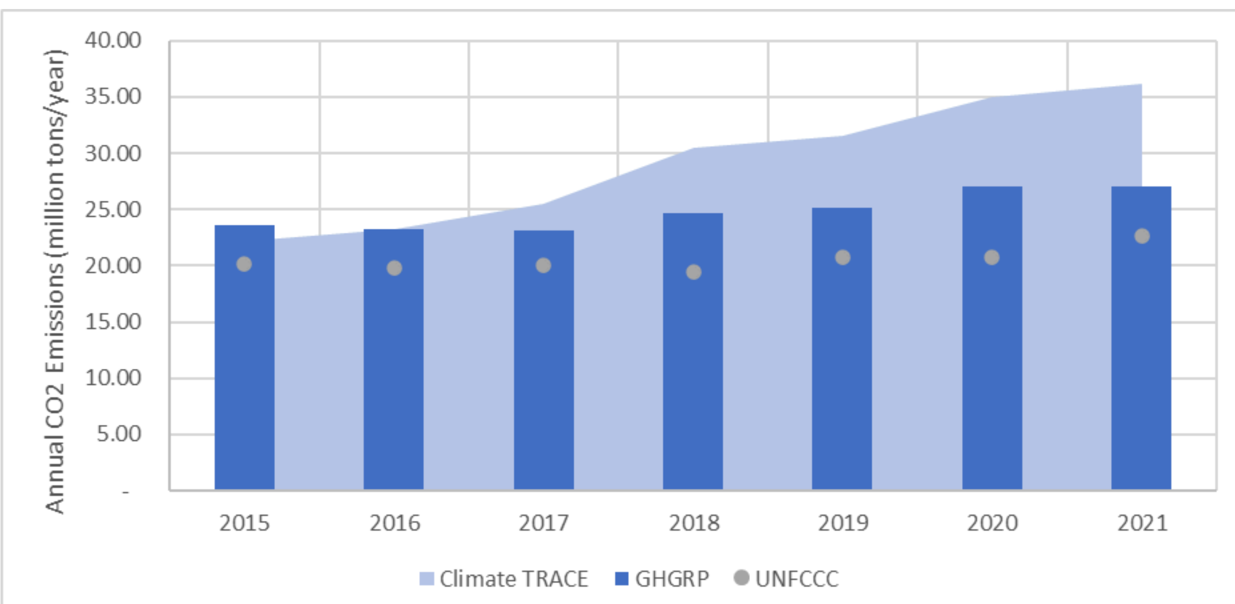

Figure 4. U.S. GHGRP, UNFCCC, and TRACE emission comparisons for years 2015 to 2021. Up to 2021 was compared since that is the most recent UNFCCC data.

Climate 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, Climate TRACE emissions estimates show a proportional increase in associated emissions and UNFCCC and 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. Climate TRACE estimates both flaring and process heat emissions. The majority of emissions from ethylene production comes 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 left room for interpretation which has led to this reporting discrepancy and the large delta between Climate 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 Climate 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. Climate 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.

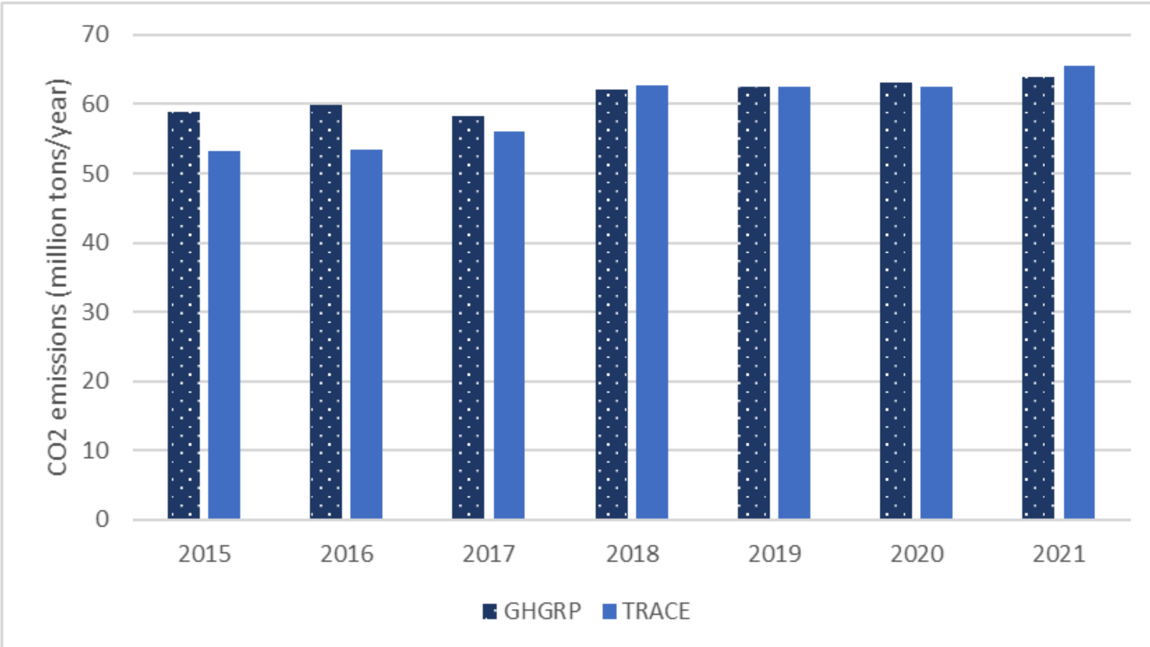

Figure 5. U.S. GHGRP (dark blue bars with white dots) adjusted and TRACE (light blue bars) emissions comparisons for years 2015 to 2021. Up to 2021 was compared since that is the most recent UNFCCC data.

Limited data availability on ethylene production emissions globally prevented comparison of TRACE results to other regions. Additional transparency in both UNFCCC reported data and non-Annex 1 countries would enable greater comparability for confirmation of modeled TRACE results.

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 value comparable to other academically reviewed papers' emissions factors and provide transparency into emissions calculations. While these emission factors are a good starting point, more robust process modeling like 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 vary greatly by region, especially related to feedstock type at a site, which can significantly impact emissions calculation. This potentially results in emissions estimates that potentially be 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 (Visible Infrared Imaging Radiometer Suite) flaring data, ethylene steam cracking does not currently include any remote sensing data that can be used to capture on-site behavior to improve emissions estimates.

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 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 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. For example, in the future we would like to incorporate flaring satellite data into our flaring factor to provide more accurate emissions estimates.

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 S1, S2 and S3 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	*2015-2023*
Temporal Resolution	*Annual*
Data format(s)	*CSV*
Coordinate Reference System	*EPSG:4326, decimal degrees*
Number of assets/countries available for download and percent of global emissions (as of 2023)	*Data covers 52 countries representing 99% of global emissions and 234 assets representing 92% of global emissions*
Total emissions for 2023	*296 million tons of* CO_2e
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"*

General Description	Definition
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. See section 2.4.4 Confidence Categories for confidence definitions.

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 (2024). *Manufacturing and Industrial Processes sector- 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.

References

1. National Bureau of Statistics China (2023). National Statistics Network Direct Reporting Portal; National Bureau of Statistics China. https://data.stats.gov.cn/easyquery.htm?cn=C01
2. American Chemistry Council. (2023). *2023 Guide to the Business of Chemistry* (pp. 85–86) [Review of *2023 Guide to the Business of Chemistry*]. https://www.americanchemistry.com/content/download/14468/file/2023-Guide-to-the-Business-of-Chemistry.pdf
3. Amghizar, I., Dedeyne, J. N., Brown, D. J., Marin, G. B., & Geem, K. M. V. (2020). Sustainable innovations in steam cracking: CO2 neutral olefin production. *Reaction Chemistry & Engineering*, *5*(2), 239–257. https://doi.org/10.1039/C9RE00398C
4. Australian Government Department of Climate Change, Energy, the Environment and Water (2023) *Vol National Inventory Report 2021.*, *The Australian Government Submission to the United Nations Framework Convention on Climate Change*. rep. Available at: https://unfccc.int/documents/627765.
5. Bergerson, J. (2022). *PRELIM: The Petroleum Refinery Life Cycle Inventory Model* [Review of *PRELIM: The Petroleum Refinery Life Cycle Inventory Model*]. University of Calgary. https://www.ucalgary.ca/energy-technology-assessment/open-source-models/prelim
6. CEFIC (2023) *2023 facts and figures of the European Chemical Industry*, *cefic.org*. Available at: https://cefic.org/a-pillar-of-the-european-economy/facts-and-figures-of-the-european-chemical-industry/
7. Department for Business, Energy & Industrial Strategy. 2023. Review of *UK Greenhouse Gas Inventory, 1990 to 2019*. https://unfccc.int/documents/627789
8. EIA. (2023). *Ethylene Crackers* [Review of *Ethylene Crackers*]. EIA U.S. Energy Atlas. https://atlas.eia.gov/datasets/2a3894eae1df438fab70d6f6f0a8867f/explore
9. Environment and Climate Change Canada (2023) *NATIONAL INVENTORY REPORT 1990 –2019: GREENHOUSE GAS SOURCES AND SINKS IN CANADA*. rep. Available at: https://unfccc.int/documents/627833
10. Environmental Protection Agency (2023. *EPA Facility Level GHG Emissions* [Review of *EPA Facility Level GHG Emissions*]. https://ghgdata.epa.gov/ghgp/main.do
11. Federal Environment Agency (2023) *Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol 2021 National Inventory Report for the German Greenhouse Gas Inventory*. rep. Available at: https://unfccc.int/documents/627785.
12. Federal Ministry of Climate Action, Environment, Energy, Mobility, Innovation and Technology (2023) *AUSTRIA'S NATIONAL INVENTORY REPORT 2022 Submission under the United Nations*

Framework Convention on Climate Change and under the Kyoto Protocol. rep. Available at: https://unfccc.int/documents/627757
13. Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet). 2023. Review of *NATIONAL REPORT on the INVENTORY of Anthropogenic Emissions from Sources and Removals by Sinks of Greenhouse Gases Not Controlled by the Montreal Protocol for 1990 - 2019*. https://unfccc.int/documents/631719
14. Gelder, A (2023, April 25) *Refinery-petrochemical integration disrupts gas-based cracker feedstock advantage | Wood Mackenzie*. Www.woodmac.com. https://www.woodmac.com/news/opinion/refinery-petrochemical-integration-gas-based-cracker-feedstock/
15. IEA (2022) *World Energy Outlook 2022*. https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf
16. IPCC (2006) *Ethylene* [Review of *Ethylene*]. Emissions Factor Database; IPCC. https://www.ipcc-nggip.iges.or.jp/EFDB/find_ef.php?ipcc_code=2.B.8.b&ipcc_level=3
17. IPCC (2006) *2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 3 Industrial Processes and Product Use* [Review of *2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 3 Industrial Processes and Product Use*]. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/3_Volume3/V3_3_Ch3_Chemical_Industry.pdf
18. Ministère de la Transition Écologique (2023) *Rapport National d'Inventaire pour la France au titre de la Convention cadre des Nations Unies sur les Changements Climatiques et du Protocole de Kyoto*. rep. Available at: https://unfccc.int/documents/627737
19. Ministry of the Environment, Japan Greenhouse Gas Inventory Office of Japan (GIO), CGER, NIES (2023) *National Greenhouse Gas Inventory Report of JAPAN 2021*. rep. Available at: https://unfccc.int/documents/627900
20. National Institute for Public Health and the Environment (2023) *Greenhouse gas emissions in the Netherlands 1990–2019 National Inventory Report 2021*. rep. Available at: https://unfccc.int/documents/627759
21. Petrochemicals Europe (n.d.) *Cracker Capacity* [Review of *Cracker Capacity*]. https://www.petrochemistry.eu/about-petrochemistry/petrochemicals-facts-and-figures/cracker-capacity/
22. Transparency International (2023) *Corruption Perceptions Index*. Transparency International. https://www.transparency.org/en/cpi/2023
23. Sarin, S., & Singh, R (2022) *Net-zero carbon ethylene production via recovery of CO 2 from cracking furnace flue gas Process Economics Program*. https://cdn.ihsmarkit.com/www/pdf/0722/RW2022-03_toc.pdf
24. Sphera (2022, April 7) *Life Cycle Assessment of Chemical Recycling for Food Grade Film* [Review of *Life Cycle Assessment of Chemical Recycling for Food Grade Film*]. Consumer Goods Forum. https://www.theconsumergoodsforum.com/wp-content/uploads/2022/04/Life-Cycle-Assessment-of-Chemical-Recycling-for-Food-Grade-Film.pdf
25. Statistics Finland (2023) *GREENHOUSE GAS EMISSIONS IN FINLAND 1990 to 2019*. rep. Available at: https://unfccc.int/documents/627718
26. Swedish Environmental Protection Agency (2023) *National Inventory Report Sweden 2021 Greenhouse Gas Emission Inventories 1990-2019*. rep. Available at: https://unfccc.int/documents/627663
27. The Institute for Environmental Protection and Research. 2023. Review of *Italian Greenhouse Gas Inventory 1990-2019. National Inventory Report 2021*. https://unfccc.int/documents/627845
28. Turkish Statistical Institute (2023) *April 2021 TURKISH GREENHOUSE GAS INVENTORY 1990 - 2019*. rep. Available at: https://unfccc.int/documents/627786.
29. United States Environmental Protection Agency. 2023. Review of *Inventory of U.S. Greenhouse Gas Emissions and Sinks*. https://unfccc.int/documents/627784