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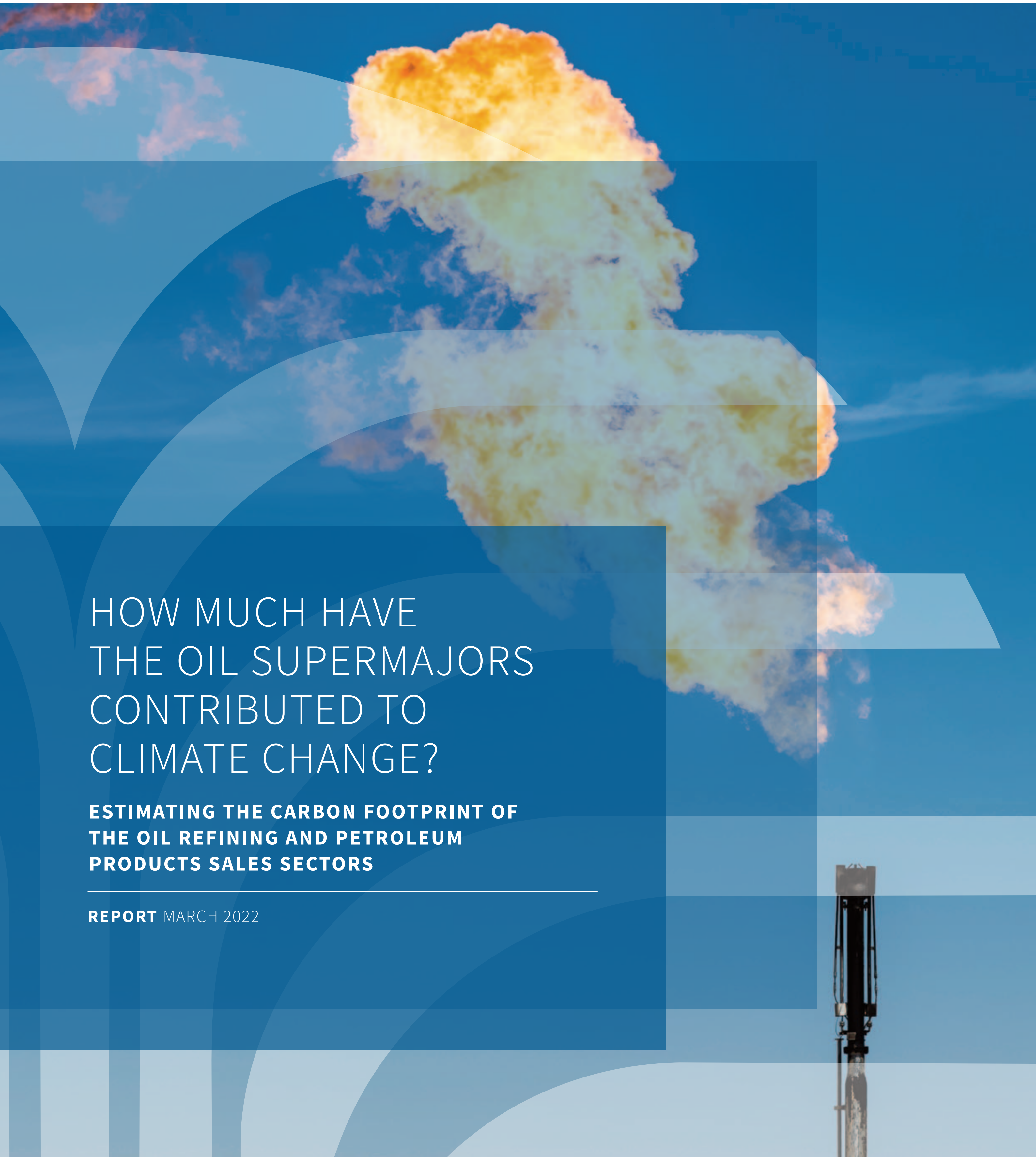

HOW MUCH HAVE THE OIL SUPERMAJORS CONTRIBUTED TO CLIMATE CHANGE?

ESTIMATING THE CARBON FOOTPRINT OF THE OIL REFINING AND PETROLEUM PRODUCTS SALES SECTORS

REPORT MARCH 2022

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Acknowledgments

This report was authored by Jiarui Chen, Perrine Toledano, and Martin Dietrich Brauch.

The authors are extremely grateful to Richard Heede's in-depth review and comments and to Michael Burger and Tom Mitro for their valuable inputs.

The authors also thank Jack Nicholas Arnold and Yechan Lee for their assistance in research and design.

This report was commissioned by the MacArthur Foundation.

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Suggested citation: Jiarui Chen, Perrine Toledano, and Martin Dietrich Brauch. *How Much Have the Oil Supermajors Contributed to Climate Change? Estimating the Carbon Footprint of the Oil Refining and Petroleum Product Sales Sectors*. New York: Columbia Center on Sustainable Investment (CCSI), March 2022. https://ccsi.columbia.edu/content/oil-supermajors-carbon-footprint-refining-sales-climate-change.

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LIST OF ACRONYMS AND ABBREVIATIONS

AIC	Akaike information criterion
API	American Petroleum Institute
BOE	Barrels of Oil Equivalent
BUR	Biennial Update Reports
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
EPA	U.S. Environmental Protection Agency
EIA	U.S. Energy Information Administration
FCC	Fluid catalytic cracking
GHG	Greenhouse gas
GOR	Gas-to-oil ratio
GREET	Greenhouse Gases, Regulated Emissions, and Energy use in Transportation
GWP	Global Warming Potential
H_2	Hydrogen
H_2O	Water
IPCC	Intergovernmental Panel on Climate Change
IPIECA	International Petroleum Industry Environmental Conservation Association
JV	Joint Venture
LPG	Liquefied petroleum gas
M	Million
M&A	Merger and Acquisition
Mt	Million metric tonnes
NHSTA	National Highway Traffic Safety Administration
NIR	National Inventory Report
OCI	Oil-Climate Index
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
OPEM	Oil Products Emissions Module
OPGEE	Oil Production Greenhouse Gas Emissions Estimator
PRELIM	Petroleum Refinery Life Cycle Inventory Model
SOR	Steam oil ratio
UNFCCC	United Nations Framework Convention on Climate Change
VFF	Venting, flaring, and fugitives
WOR	Water-to-oil ratio
WRI	World Resources Institut

SUMMARY

In the 40-year period 1980–2019, annual carbon dioxide (CO_2) emissions from fossil fuel combustion, including flaring, increased by more than 80%, and total emissions from those sources represented approximately 83% of anthropogenic CO_2 emissions (also including cement production and land-use change) without accounting for sinks. Understanding the carbon footprint of countries and companies along the oil value chain is fundamental to outlining paths to reduced reliance on fossil fuels. However, academic analyses of carbon footprints are limited by the lack of a reliable dataset and carbon accounting method that would allow comparisons across countries and companies.

A pioneering 2014 upstream-focused study by Richard Heede quantified the historical contribution of the "carbon majors" to global CO_2 and methane (CH_4) emissions from 1751 to 2010, tracing 63% of cumulative global emissions to 90 upstream fossil fuel companies (including oil, gas, and coal) and cement companies. A focus on their extraction-based activities does not offer insights into the full scale of their hold on oil value chains. This paper sheds light on their contribution to emissions from the midstream and downstream levels of the value chain.

Our study estimates the global carbon footprint of the oil refining and petroleum sales sectors, adopting a supply-chain approach. The study also assesses the life-cycle greenhouse gas emissions from the oil refining and petroleum products sales businesses of the "Oil Supermajors"—BP, Chevron, Eni, ExxonMobil, Shell, and TotalEnergies—the six largest publicly traded oil companies by revenue and political influence.

Using a mix of quantitative methods and open-source models, we first estimate a time series (1980–2019) of country-specific life-cycle greenhouse gas emission factors for the sectors of crude oil refining and sales of petroleum products refined from crude oil (gasoline, jet fuel, diesel, fuel oil, residual fuels, and LPG), without accounting for gas value chains, for the 83 countries that jointly accounted for 93% of the global crude oil refining throughput in 2015. We then estimate the global and country-level carbon footprints of the two sectors based on the emission factors we estimated, global refinery outputs, and sales volume. Applying our life-cycle model to data on refinery output and sales of petroleum products, we estimate the supermajors' carbon footprints in both sectors. These carbon footprints are not meant to be added up as they overlap.

The petroleum products sales sector sold approximately 1,128 billion barrels of petroleum products from 1980 to 2019, leading to emissions of approximately 508 metric gigatons of carbon dioxide equivalent (Gt CO_2e). The sector's global carbon footprint nearly doubled in the 40-year period. The six supermajors jointly account for 35% of the cumulative global carbon footprint of the sector in the same period, evidencing that they own a sizeable share of the sector.

The oil refining sector refined approximately 985 billion barrels of crude oil from 1980 to 2019, leading to emissions of approximately 443 Gt CO_2e. The sector's global carbon footprint increased by approximately 51% in the 40-year period. The supermajors jointly account for approximately 23% of the cumulative global carbon footprint of the sector in the same period, reflecting lower but still significant market concentration.

The carbon intensities of the companies are within a narrow range, which largely results from the interconnectedness of the value chains. The supermajors refined and sold petroleum products originating from crude oil extracted by other companies. For instance, the oil used for more than 50% of Shell's sold products comes from third parties. When Shell sells these petroleum products, the carbon embedded in them comes from multiple oil fields associated with different values of API gravity, refinery efficiency, and distribution distance. The API gravity of Shell's typical oil fields as well as the impact of Shell's refinery efficiency and distribution network is diluted in a portfolio of API gravity, refinery efficiency, and distribution distance values associated with oil coming from other companies.

The report also scrutinizes companies' emissions accounting methods and concludes that company numbers rely on various and not fully transparent reporting boundaries, volume, and emission accounting methodologies. Most problematic is that most supermajors fail to report scope 3 emissions comprehensively; there is also a lack of time-series data on scope 3 emissions. In addition, the volume and emission accounting method might underestimate emissions in three ways: by omitting the emissions of third parties in the company's value chain (e.g. when a company sells petroleum products produced and refined by other companies or when it refines products later sold by other companies), playing with boundaries, or omitting data from non-operated joint ventures.

While our estimation addresses some limitations of company emissions reporting, our methodological approach still presents its own limitations, attesting to the lack of data transparency and standardized carbon accounting at both country and corporate level, which prevents informed decision-making on those holding the levers of influence on companies: investors, consumers, and policy makers. Without consistent and transparent emission accounting, companies' net-zero commitments and targets are meaningless. To address these limitations, the Coalition on Material Emissions Transparency (COMET), supported by the secretariat of the United Nations Framework Convention on Climate Change (UNFCCC), will create a harmonized greenhouse gas calculation framework applicable to all mineral and industrial supply chains.

INTRODUCTION

Fossil fuel combustion, including flaring, accounts for approximately 68% of cumulative global anthropogenic emissions of carbon dioxide (CO_2), the most prominent greenhouse gas (GHG) causing global warming. Between 1980 and 2019 alone, the 40-year period of study in this report, annual CO_2 emissions from those sources increased by more than 80%, and total emissions from those sources represented approximately 83% of anthropogenic CO_2 emissions (also including cement production and land-use change) without accounting for sinks[1] (Global Carbon Project 2021). Understanding the carbon footprint of countries and companies along the oil value chain is fundamental to understanding the paths to reduced reliance on fossil fuels. However, academic analysis of carbon footprints to date has lacked a reliable set of data and a reliable carbon accounting method that allows comparisons across countries and companies.

Indeed, developing and applying such a method poses various challenges. For long, academic literature focused more on calculating the carbon footprint of individual market segments along the oil value chain than on estimating the life-cycle carbon footprint of petroleum products (Gordon et al. 2015). Only in 2011 did the World Resources Institute (WRI) release an internationally accepted accounting standard under the GHG Protocol (Gillenwater 2015) to calculate scope 3 emissions, defined as emissions from sources that the reporting entity does not own or directly control (Bhatia et al. 2011). In addition, certain Non-Annex I countries,[2] such as China and Saudi Arabia, are crucial crude oil refining and consuming countries but have less standardized emission reporting than Annex I countries (Heede 2014).[3] As a result, there is a lack of time-series data for scope 3 emissions from the oil industry, and the understanding of the GHG emissions attributable to the oil refining and petroleum sales segments of the oil value chain is currently underdeveloped.

In a pioneering attempt to address these issues, Heede (2014) quantified the historical contribution of the "carbon majors"[4] to global CO_2 and methane (CH_4) emissions from 1751 to 2010. The study traces 63% of cumulative global emissions to 90 upstream fossil fuel companies (including oil, gas, and coal) and cement companies.

Differently from Heede's (2014) extraction-based analysis, our study estimates the global carbon footprint of the oil refining and petroleum sales sectors adopting a supply-chain carbon-footprint approach. We leverage existing open-source academic models but extend their time series and increase the number of countries covered. In addition, our study focuses on assessing the life-cycle GHG emissions from the oil refining and petroleum products sales businesses of "supermajors"—BP, Chevron, Eni, ExxonMobil, Shell, and TotalEnergies—the six largest publicly traded oil companies by revenue and political influence.[5]

For the avoidance of doubt, this study neither adopts a scope-based approach nor addresses the accounting challenges of such an approach. Our study assesses the life-cycle GHG emissions: all emissions released throughout the value chain of a barrel of oil, from upstream exploration to final combustion. In addition to a company's own value chain emissions, this method enables us to estimate the emissions from barrels of oil that the company refined or sold, including oil extracted by other companies.

Using a mix of quantitative methods detailed in Section 2, we first estimate a time series of country-specific life-cycle GHG emission factors for the sectors of crude oil refining and sales of petroleum products[6] refined from crude oil, covering the period 1980–2019 and including 83 countries. We then estimate the global and country-level carbon footprints of the oil refining and petroleum products sales sectors based on the emission factors we derived, global refinery outputs, and sales volume. Finally, we estimate the share of the six supermajors in those footprints, using their sales volumes, refinery outputs, and operating locations.

FOOTNOTES

[1] Sinks include oceans and forests as well as cement carbonation, which absorb and capture CO_2 from the atmosphere and reduce its atmospheric concentration.

[2] The 160 Non-Annex I Parties to the UNFCCC (most of them developing countries) are not required to submit National Inventory Reports (NIRs) every year but must submit Biennial Update Reports (BURs), including a national inventory report and information on mitigation actions.

[3] Annex I Parties include Organisation for Economic Co-operation and Development (OECD) countries plus other developed countries and economies in transition.

[4] Fossil fuel companies that produced more than 8 million metric tons of carbon per year.

[5] The first four originated from a group of seven companies known as "Seven Sisters" (BP, Chevron, ExxonMobil, Shell, Gulf, and Texaco) (Anthony 1976); after successive mergers and acquisitions, the Seven Sisters are now four of the so-called supermajors group. Eni and TotalEnergies have also been considered supermajors (Statista 2021). ConocoPhillips is only seldom included in the list of supermajors since it spun off its downstream operations (OilNow 2017).

[6] The petroleum products studied in this paper are gasoline, jet fuel, diesel, fuel oil, residual fuels, and LPG refined from crude oil.

METHODOLOGY

METHODOLOGICAL STEPS

The broad methodological steps followed in this paper are described as follows, with detailed methodological explanations regarding each of the steps outlined below in the specific sections that present the research outcomes.

1. We gather production data, including volume, carbon intensity, API gravity,[7] sulfur[8] in the sectors of crude oil refining, and sales of petroleum products refined, from crude oil in the selected 83 countries from the supplementary information of the research paper by Jing et al. (2020), which builds on Wood Mackenzie (2015). The dataset covers 93% of the global crude oil refining throughput in 2015 and is therefore representative of the global oil refining sector. Emissions from fossil gas are not within the scope of this study. Emissions from products other than crude oil in the upstream industry, such as petrochemicals and lubricants, are also not within the scope of this study.[9]

2. We build our estimation model on five open-source models that are commonly used in academic papers: (1) the Oil Production Greenhouse Gas Emissions Estimator (OPGEE) Model to estimate upstream emission factors (El-Houjeiri and Brandt 2017), (2) the Petroleum Refinery Life Cycle Inventory Model (PRELIM) to estimate mid-stream emission factors (Abella, Motazedi, and Bergerson 2015), and (3) the Oil Products Emissions Model (OPEM) to estimate downstream emission factors (Gordon 2016). We also refer to the Oil-Climate Index (OCI) Model to aggregate life-cycle emission factors (Gordon et al. 2015) and the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) Model to obtain parameters for deriving time-series emission factors (Cai, Sykora, and Wang 2021).
3. We break down life-cycle GHG emission factors by the upstream, midstream, and downstream oil sectors following the stages and boundaries defined in Section 2.2,[10] setting up the framework to estimate GHG emission factors (Section 3.1, 4.1, and 5.1, respectively). The framework includes the stages of emissions in each sector, emission sources, determining factors,[11] formulas, and default emission factors.
4. For each sector of the oil value chain (upstream, midstream, and downstream), we assess the statistical significance of certain factors to GHG emission factors by running univariate regressions for each of these determining factors (Sections 3.2, 4.2, and 5.2, respectively). Since the regression results reveal that API gravity is statistically significant in determining the emission factors of most stages of the three sectors of the oil value chain,[12] we adopt API gravity as the determining factor to estimate country-specific emission factors. The 83 countries in our sample are "destination countries"[13] (Jing et al. 2020) and, for this reason, are given the API gravity characterizing the crude oil they are importing to feed their refineries.
5. For each stage of the value chain, we estimate country-specific emission factors by applying the decision-tree model, a machine learning model that predicts results by categorical independent variables (Sections 3.2.2, 4.3, and 5.2). The model learns relationships between API gravity and other stage-specific parameters in the OCI sample consisting of 71 fields for which there is consistent and quality data, which then enables us to extrapolate the relationship in the context of the 83 countries.
6. To estimate the change in upstream emission factors throughout time, we use the 25-year change of emission factors of representative oil fields (Masnadi and Brandt 2017). We also estimate the change in Vented, Flaring, and Fugitive (VFF) emissions[14] in the upstream sector based on the time-series change of VFF emission factors in the United States. We estimate the change in midstream emission factors throughout time based on the time-series change of API gravity and sulfur content in the United States. We also derive the time-series change of default emission factors calculated by the U.S. Environmental Protection Agency (EPA) to update the parameters in model estimation and adjust the change in emission factors in the three sectors throughout time (Sections 3.3, 4.4, and 5.3).
7. We compute life-cycle emission factors for each country and over time by summing up the emission factors throughout the three stages of the oil value chain.
8. To assess the supermajors' contribution to GHG emissions, we first collect data on refinery output, petroleum products sales, and geographic distribution of sales of the six supermajors, based on corporate reports and commercial databases. We apply our life-cycle emission factors to the data on the companies' oil refining and petroleum products sales by country and year to estimate the carbon footprint of their oil refining and petroleum products sales sectors (Section 6). These two types of carbon footprints are separate and not cumulative.

FOOTNOTES

[7] American Petroleum Institute (API) gravity is a measure of a petroleum liquid's density relative to that of water (Ernest, et al. 1959).

[8] Sulfur content is expressed as the percentage of sulfur in crude oil, which is a measure of its purity.

[9] For instance, the OPGEE model doesn't include GHG emissions from condensates of light liquids that can be separated and sold before oil is transported to a refinery or emissions from co-products like petcoke that are associated with upgrading heavy oils upstream of the refinery.

[10] We consider the stages of emissions in each sector as commonly defined by government agencies (the U.S. Environmental Protection Agency [EPA]), intergovernmental organizations (the Intergovernmental Panel on Climate Change [IPCC]), industry associations (the American Petroleum Institute [API]), and academic literature.

[11] Factors that determine the GHG emissions, including oil field characteristics, production techniques, crude oil grades, refinery configuration, transportation modes, etc. (as explained in the following sections).

[12] API is statistically significant to the production, drilling, and processing stages in the upstream sector and to total refining emissions and product types in the downstream sector.

[13] Destination countries/regions represent the locations where refined products are sold. Thus, the data takes into account the import/export of refined products when calculating transportation from the refining sector to the petroleum products sales sector.

[14] See definition in footnote 17.

STAGES AND BOUNDARIES

As per the OCI model (Gordon et al. 2015), we define in Table 1 the stages and the activities within each stage in our life-cycle model.

All activities within the oil value chain are allocated into one of these 12 stages; we therefore cover the entire oil value chain, without overlap between stages. The emission factor associated with each stage only covers the emissions of the specific stage, eliminating the risk of double counting.

TABLE 1: STAGES AND BOUNDARIES OF THE LIFE-CYCLE MODEL

SECTOR	STAGE	ACTIVITIES WITHIN STAGE
Upstream	Exploration	Clearing land, seismic survey and drilling exploratory wells
	Drilling & development	Drilling production wells, installing equipment
	Production & extraction	Lifting fluids and injecting fluids, flooding, gas flooding, steam flooding
	Surface processing	Seperating the fluids into streams of oil, gas and water
	Maintenance	Maintaining compressors, wells, and pipelines
	Waste Disposal	Disposing waste produced in upstream operations
	Transport to refinery	Transporting cruide oil from upstream production facility to refinery
Midstream	Separation	Piping crude oil through hot furnaces, discharging liquids and vaports, seperating liquids and vapors into different petroleum components
	Conversion	Processing low-value petroleum components into higher-value petroleum products
	Treatment	Making gasoline, diesel and kerosene
Downstream	Transport to retail	Transporting crude oil from refinery facility to retail market (gas station etc.)
	Combustion	Petroleum products used by end users

Source: Adapted from Gordon et al. (2015).

PART 1

UPSTREAM SECTOR

1.1. STAGES AND EMISSION SOURCES WITHIN THE UPSTREAM SECTOR

Upstream sector emissions are defined as “GHG emissions of crude petroleum unearthed, processed, and delivered to the refinery entrance” (International Petroleum Industry Environmental Conservation Association [IPIECA] 2011). Following the OPGEE model and as also shown above in Table 1, we break down upstream emissions into seven stages (El-Houjeiri and Brandt 2017):

1. Exploration: emissions, including fugitive emissions, that occur during exploring events such as clearing land, seismic survey, and drilling exploratory wells.
2. Drilling & Development: emissions that occur during drilling and developing events such as drilling wells and installing equipment. Emissions from land-use impacts also occur since drilling releases biogenic carbon from disturbed ecosystems and soils.
3. Production & Extraction: emissions that occur during the work to lift fluids and inject fluids, flooding, gas flooding, and steam flooding.

4. Surface Processing: emissions that occur during the processing of crude oil and associated gas.
5. Maintenance: venting and fugitive emissions that occur in maintaining compressors, wells, and pipelines. Rather than calculating maintenance emissions as a separate stage, the OPGEE model includes maintenance emissions from drilling, production, and processing equipment in the corresponding stages to simplify calculation.
6. Waste Disposal: emissions from waste disposal in the upstream operations. Since the emissions are below the statistical significance threshold, OPGEE does not model them.
7. Transport: emissions that occur due to energy consumption by transporting crude oil from an upstream production facility to a refinery. Transport modes include pipelines and rail for land transport and ocean tankers and barges for inter-continental transport. Fugitive emissions occur during loading and unloading products.

Within each stage of the upstream sector, emissions come from three main sources (El-Houjeiri and Brandt 2017):

1. Combustion: emissions from direct combustion in energy use.
2. Land Use: emissions from land-use change, which is determined by ecosystem carbon richness and field development intensity.
3. Venting, Flaring, and Fugitives (VFF): Venting and fugitive emissions are the emissions of non-combusted hydrocarbons. Venting emissions happen predictably during maintenance, while fugitive emissions happen unpredictably due to the depreciation of machines, among other factors.[15] Flaring emissions occur during the burning of the associated gas that cannot be used economically. VFF emissions can be considerably reduced with a stringent regulatory framework (Banerjee and Toledano 2016).[16]

TABLE 1: STAGES WITHIN THE UPSTREAM SECTOR

OPGEE (UPSTREAM)							
STAGE	**COMBUSTION**	**LAND USE**	**VFF**			**TOTAL**	**NOTE**
			Venting	Flaring	Fugtives		
Exploration						A	
Drilling & Development						B	
Production & Extraction						C	
Surface Processing						D	
Maintenance	NA	NA	NA	NA	NA	NA	As explained in above text
Waste disposal	NA	NA	NA	NA	NA	NA	As explained in above text
Transport						E	
Total						F=A+B+C+D+E	

Source: El-Houjeiri and Brandt 2017.

FOOTNOTES

[15] "Leaking equipment and tanks, well workovers and cleanups, compressor startups and blowdowns, pipeline maintenance, gas dehydrators, acid gas recovery units, well cellars, separators (wash tanks, free knock outs, etc.), sumps and pits, and components (valves, connectors, pump seals, flanges, etc.)" (El-Houjeiri and Brandt 2017).

[16] Under the setting of the OPGEE model, VFF emissions are allocated in the corresponding stage of the upstream sector. So when we apply a machine learning model to generate the relationship between API gravity and the emission factors of each stage in the upstream sector, VFF emissions are embedded.

1.2. KEY PARAMETERS

1.2.1. Literature Review

The key variables that determine upstream emission factors include oil field properties, control parameters in production and processing stages, parameters about land-use impact, transport modes, and distance of crude oil transportation, as summarized in Appendix 7.

Table 3 shows the stages of the upstream segment that are impacted by these key variables, adapted from El Houjeiri and Brandt (2017).

1.2.2. Estimation of Country-Specific Emission Factors

To estimate country-specific emission factors for the upstream sector, we proceed in four steps.

We first determine the statistical relationship between upstream emission factors and the key parameters to prepare the estimation based on statistically significant key parameters. To this end, we use the OCI sample, which includes quality and consistent data from 71 global oil fields (Gordon et al. 2015).

TABLE 3: KEY PARAMETERS WITHIN THE UPSTREAM SECTORS

VARIABLES	UPSTREAM SEGMENTS (STAGES)				
	Exploration	Drilling	Production	Processing	Transport to Refinery
Field depth	X	X	X		
Offshore	X				
Field production rate	X	X	X	X	X
Location		X			
API		X	X	X	X
Number of producer & injector wells		X	X		
Crude ecosystem carbon richness		X			
Field development intensity		X			
Diameter			X		
Productivity index			X		
Average reservoir pressure			X		
Gas position			X		
Gas-oil ratio (GOR)			X		
Water oil ratio (WOR)			X		
Water injection ratio			X		
Steam oil ratio (SOR)			X		
Fraction of remaining gas to reinjection			X		
Fraction of water to reinjection/flooding			X		
Fraction of electricity generated from cogen			X		
Heater/treater			X		
Stabilizer			X		
Fraction of oil transported by each mode					X
Transport distance (one way)					X
Ocean tanker size					X

Source: Adapted from El-Houjeiri and Brandt (2017).

TABLE 4: OIL FIELDS IN OCI DATASET BY REGIONS AND CRUDE OIL TYPES

# OF OIL FIELDS	LIGHT	MEDIUM	HEAVY
Africa	4	7	0
Asia & Pacific	9	2	1
Europe	0	3	1
Middle East	8	7	0
North America	1	16	2
South America	5	1	4

TABLE 5: PREDICTED VALUES IN THE MACHINE LEARNING MODEL

Kg CO_2e/bblCrude	LIGHT OIL (API > 32)	MEDIUM OIL (22 < API ≤ 32)	HEAVY OIL (API ≤ 22)
Drilling	5.5817	3.8527	12.2882
Production	10.2579	14.3950	30.4177
Processing	10.2958	4.4937	4.4446

We run a univariate regression of each key parameter for emission factors from the drilling, production, processing, and transporting stages and the total upstream emission factors. Our results show that API gravity is statistically significant in determining drilling, production, and processing emission factors at a 5% significance level and is, therefore, a useful parameter for estimating the emission factors of the first three stages of the upstream sector. Other key parameters are statistically significant, but none of them affects all three stages (see Appendix 8).

Since API gravity is statistically significant, we create a categorical variable that corresponds to crude oil classification based on API gravity:

- Light oil: API gravity > 32
- Medium oil: 32 ≥ API gravity > 22
- Heavy oil: API gravity ≤ 22

The classification is aligned with the default values of the OPGEE Model and the PRELIM Model (U.S. Energy Information Administration 2020a).

The distribution of the 71 oil fields of the OCI sample by geography and type of crude oil is shown in Table 4. Appendix 1 summarizes the sample dataset.

As a second step towards estimating the country-specific emission factors, we build on the 2015 data of 343 global crude oil fields in 66 source countries (oil-producing countries) and 478 refineries in 83 destination countries (oil-consuming countries) (Jing et al. 2020). The dataset contains weighted-average volume refined, API gravity, and sulfur content. The status of a country as a source or destination country impacts the API gravity, which in turn impacts the country-specific emission factor: the emission factor for a source country will depend on the API gravity of its own fields, and the emission factor for a destination country will depend on the API gravity of the fields in the origin countries.

In a destination country, the estimated emissions intensity is that associated "with all crude oil refined in that country, including domestically produced and imported crude oil." In a source country, the estimated emissions intensity is that "associated with refining all crude oil produced in that country, even if refining occurs in other countries" (Jing et al. 2020).

For instance, China is the world's fifth crude oil–producing country and one of the largest crude oil–importing countries. In 2015, China imported 40% of the crude oil it refined from members of the Organization of the Petroleum Exporting Countries (OPEC) and 10% from Russia (Jing et al. 2020). The volume weighted-average API gravity of China as a destination country is 29.0 and as a source country, 30.6.

Because our perspective is to follow the barrel of oil up and down the value chain from either the refinery point or the gas station point, throughout this paper we use the parameters for destination countries, so that we take into account the import and export of crude oil into and out of the country where the refinery or the petroleum product sales outlet is located.

The dataset has upstream emission factors for 55 destination countries. We use a statistical machine-learning model to estimate the upstream emission factors for the remaining 28 countries.

This machine-learning model is a non-parametric supervised learning classification and regression model. It creates a prediction model by learning decision rules for target variables based on the categorical variable. It requires less data pre-processing and handles both numerical and categorical data, which is the situation in our case (Pedregosa et al. 2011).

The model here learns the relationship between API gravity and emission factors for the drilling, production, and processing stages in the OCI sample in order to predict the upstream emission factors for the 28 countries according to their API gravity as destination countries (see Table 5).

The energy used to extract and process one barrel of heavy oil is equivalent to 1/3 barrel of light oil. More energy is needed for direct heating when transporting heavy oil by pipeline (Riva

TABLE 6: REGIONAL FLARING INTENSITY

REGIONS	FLARING INTENSITY (Tons of Hydrocarbon flared per kilotons of Hydrocarbon produced)	WEIGHTED AVERAGE (by production rate)) API
Africa	39.42	36
Asia & Pacific	19.22	42
Europe	3.77	31
Middle East	5.72	33
North America	8.74	31
South America	6.89	30
Correlation	51.67%	

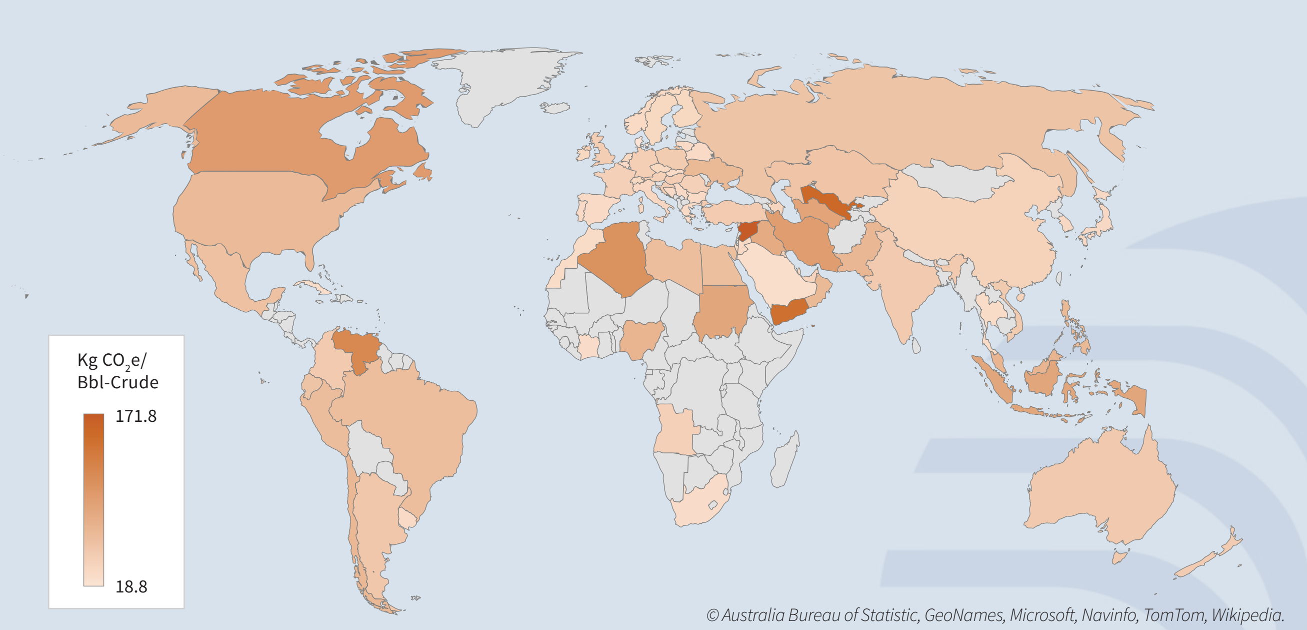
Data source: Flaring intensity from International Association of Oil & Gas Producers (2016), weighted average API is calculated by the authors based on the OCI dataset.

and Atwater 2016). Thus, as intuitively expected, the predicted emission factors of the drilling and production stages of heavy oil fields (lower API gravity) are higher than those of light oil fields (higher API gravity). However, processing emission factors are higher in light oil fields than in heavy oil fields. The reason for this relates to the geographic distribution of oil types and flaring facilities in our sample. On one hand, in the OCI dataset used, oil fields located in developed country markets have heavier oil (lower API gravity) on average. On the other hand, the oil fields in developed country markets, induced by stricter regulations, operate with more advanced flaring facilities, which yield lower flaring intensity and ultimately result in lower processing emission factors. To verify the correlation between API gravity and flaring intensity, we examine the relationship between the two variables at the regional level. The correlation between regional flaring intensity and regional API in our dataset is 51.67%, which confirms that regions with higher API gravity (lighter oil) also have higher flaring intensity (see Table 6). Since oil fields located in developed country markets operate with more advanced flaring facilities, even if they have lower API gravity (that is, even if they have heavier oil), their processing emission factors are lower.

As a third step, we leverage the existing oil field–specific transport to refinery emission factors in the OCI dataset to calculate the volume-weighted average emission factors (weighted by production volume of the oil fields) from transport from oil fields to refinery for each region (Africa, Asia & Pacific, Europe, Middle East, North America, and South America). In our 83-country sample, we then apply the same emission factor for transport from oil fields to refinery to all countries within the same region, short of better data.

As a final step, we sum up the emission factors across all stages (drilling, production, processing, and transportation to refinery) to estimate a country-specific emission factor. Appendix 2 shows the final figures of the estimated upstream emission factors for all 83 countries in the sample in 2015.

FIGURE 1: UPSTREAM EMISSION FACTORS BY COUNTRY IN 2015



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1.3. CHANGE IN COUNTRY-SPECIFIC EMISSION FACTORS OVER TIME

1.3.1. Change in Combustion Default Emission Factors Over Time

The default combustion emission factors used in the current OPGEE model are the 2010 values of emission factors from the GREET model (Cai, Sykora, and Wang 2021). The default emission factors contain 41 combinations of combustion technologies and fuels at the upstream level. The GREET model simulates the evolution of technologies, enabling the introduction of cleaner technologies over time. Each combination of “technology shares” represents the technological setting (that is, the state of the technology) at that time. GREET applies technology shares to simulate the trend that future emission control technologies gradually replace the initial technologies and creates a time-series dataset for default emission factors used for calculating emissions (Cai, Sykora, and Wang 2021).

To assess the effect of the change over time in the default combustion emission factors (see Appendix 3) on total upstream emission factors, we apply them to the OPGEE model for the same 71 oil fields in the OCI sample set. OCI. The simple average total upstream GHG emission factors among the 71 oil fields remains 9.38 from 1990 to 2020., which indicates no significant change in emission factors due to the change in the default combustion emission factor. One reason may be the limited frequency of updates to the emission factors released by the IPCC (Alexander 2016). Another reason is that the improvement of emission control technologies reduced the CO_2-equivalent (CO_2e) emissions from other gases (VOC, CO, CH_4, and N_2O) while the emission factors of CO_2 for different technologies and fuels do not change significantly. Since the change in default emission factors over time is not significant, we do not include it in our estimation of change in country-specific upstream emission factors over time.

1.3.2. Change of Key Parameters Over Time

Empirical studies show that upstream emission factors increase over time as the oil field ages (Gavenas, Rosendahl, and Skjerpen 2015).

To reveal the change over time in the key parameters at work in the context of oil field aging, Masnadi and Brandt (2017) assessed a historical dataset of 25 global oilfields larger than 1 billion barrels. The results confirmed that upstream emission factors increase over time in most oil fields as they age due to diminishing reservoir pressure. Reduced pressure increases energy consumption in water injection, steam injection, and gas injection as well as increases water consumption in oil lifting and handling. The decreasing amount of oil produced also increases the emissions per unit of oil produced (Masnadi and Brandt 2017).

1.3.3. Time Series Change of VFF Emissions

VFF emissions account for a crucial proportion of upstream emissions. The production volume-weighted proportion of VFF emission factors to total upstream emission factors among the 71 oil fields in the OCI dataset is 68.28%. Empirical research reveals that VFF emission factors increased in the 2000s with the fracking boom and decreased in recent years due to the tightening of regulations worldwide (World Bank 2021). Regarding the United States, which contributed the most to the reduction of flaring intensity, the reduction of VFF emissions is due to overall stronger flaring regulations over time, which promoted the use of technology and innovation to detect methane emissions and reduce emissions from oil production. Given the significance of VFF emissions and their strong downward trend over time, it is necessary to consider the time-series change in VFF emissions in our estimation of country-specific time series of upstream emission factors.

1.3.4. Estimation of the Time Series of Country-Specific Emission Factors

To estimate the time series of country-specific emission factors in the upstream sector, considering the aging of oil fields and the VFF emissions, we proceed through two main methodological steps.

Considering the aging of oil fields

We first derive the average CO_2 emission factors (g CO_2/MJ crude petroleum) over time from the historical emission data of the 25 oil fields weighted on their yearly oil production (Masnadi and Brandt 2017). The 25 oil fields are located in 7 countries with good data quality. Short of a larger sample, we mirror the evolution of the oil fields in our 83 countries according to the evolution of these 25 oil fields. We then normalize the weighted-average emission factors in 1980 as 1 and apply the yearly change rates of the weighted upstream emission factors to our estimated country-specific emission factors in 2015 in order to derive the time-series emission factors for the 83 destination countries in our dataset from 1980 to 2020.

FIGURE 2: NORMALIZED CHANGE OF UPSTREAM EMISSION FACTORS OVER TIME

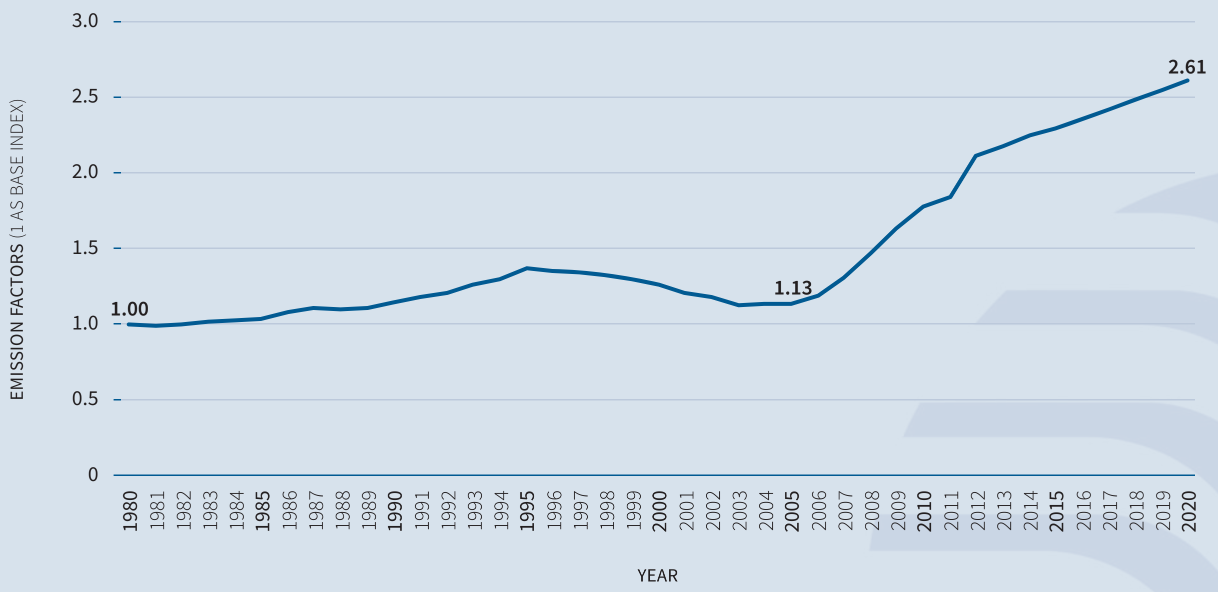


Figure 2 shows the change in normalized upstream emission factors over time. On one hand, the literature indicates that, as the oil fields become older, the emission factors tend to increase (Masnadi and Brandt 2017). The increasing trend before 1994 and after 2005 may be due to aging. On the other hand, countries may replace old oil fields with new oil fields, which have lower emission factors. The drop of upstream emission factors from 1998 to 2005 may reflect the fact that some newly discovered oil fields started to produce by the end of the 1990s and early 2000s—for example, Terra Nova (Canada) and Hibernia (Canada) in Masnadi and Brandt's (2017) sample.

Considering the change in VFF-related emissions over time

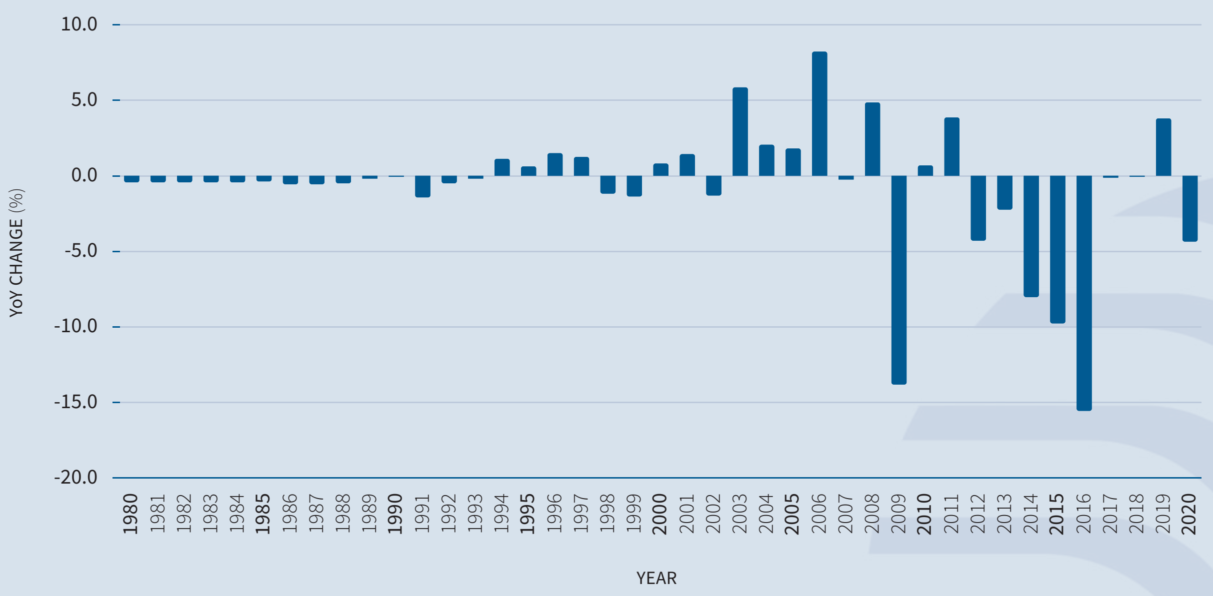
Second, we incorporate a time-series change related to VFF-related emissions. To make up for the lack of publicly available data for all countries in the sample, we adopt the time-series change in U.S. upstream VFF emission factors as the time-series change in upstream VFF emission factors for all countries. We collect the 1990–2019 U.S. upstream VFF emissions from the U.S. GHG Emissions Inventory Report (U.S. Environmental Protection Agency 2021)[17] and U.S. oil production data from BP statistics (BP 2020c). Then we calculate the year-on-year change in U.S. upstream VFF emission factors from 1990 to 2019 based on the two time-series data (U.S. VFF emissions and U.S. oil production). To address the lack of publicly available data, we adopt a 5-year rolling average of the change rates to expand the time series from 1980 to 2020.[18] As the result shows, U.S. upstream VFF emission factors had been flatted from 1980 to 2008 and decreased sharply since 2009, which aligns with the literature (see Figure 3 on the following page).

FOOTNOTES

[17] VFF Emissions from petroleum systems belong to IPCC category 1B2a, which by definition include emissions from leaks, venting and flaring associated with onshore and offshore crude oil exploration, production, and transportation to and from refineries (U.S. Environmental Protection Agency 2021). To remain in the context of the upstream stage of the oil value chain, as defined in section 2.2, we removed the refinery-related emissions.

[18] While onshore VFF could appear different than offshore VFF due to access, our estimates don't go to this level of granularity.

FIGURE 3: DATA SUMMARY OF U.S. UPSTREAM VFF EMISSIONS, OIL PRODUCTION AND YOY CHANGE OF U.S. UPSTREAM VFF EMISSION FACTORS



To have upstream emission factors reflecting change in VFF emissions over time for all 83 countries, we proceed as follows:

- We apply the production volume–weighted proportion of VFF emission factors in the total upstream emission factors from the OCI dataset to the 2015 upstream emission factors of the 83 countries to estimate the country-specific upstream VFF emission factors.
- We then apply the time-series change rate in U.S. upstream VFF emission factors to the country-specific upstream VFF emission factors in 2015 and derive a time series of country-specific upstream VFF emission factors.
- We then calculate the difference between the time series of upstream VFF emission factors and the upstream VFF emission factors in base year 2015, which reflects the change in upstream emission factors due to the change in VFF emission factors.
- Finally, we adjust the total country-specific upstream emission factors estimated in the previous step (considering aging) by adding back the difference in upstream VFF emission factors. Appendix 2 shows the full time series of estimated upstream emissions for all 83 countries in the dataset from 1980 to 2020.

FIGURE 4: VOLUME-WEIGHTED AVERAGE OF UPSTREAM EMISSION FACTORS

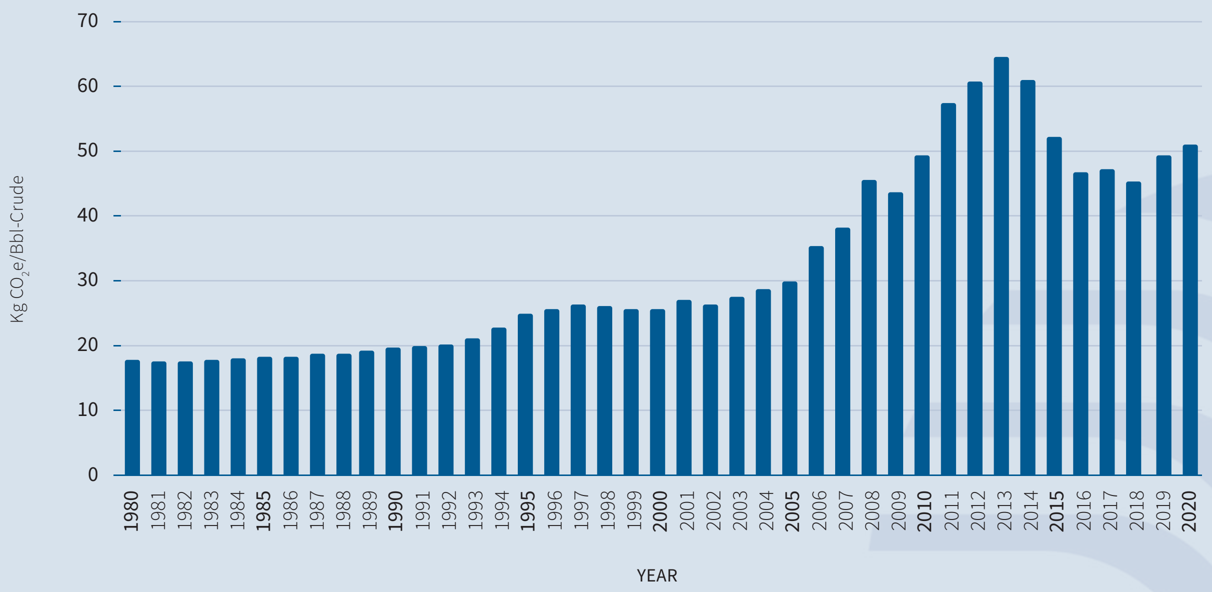


Figure 4 shows the volume-weighted average of country-specific upstream emission factors. Despite the increasing trend caused by the aging of oil fields (see Figure 2), there is a decreasing trend in upstream emission factors after 2013, which reflects the decrease of VFF-related emission factors.

PART 2

MIDSTREAM REFINING SECTOR

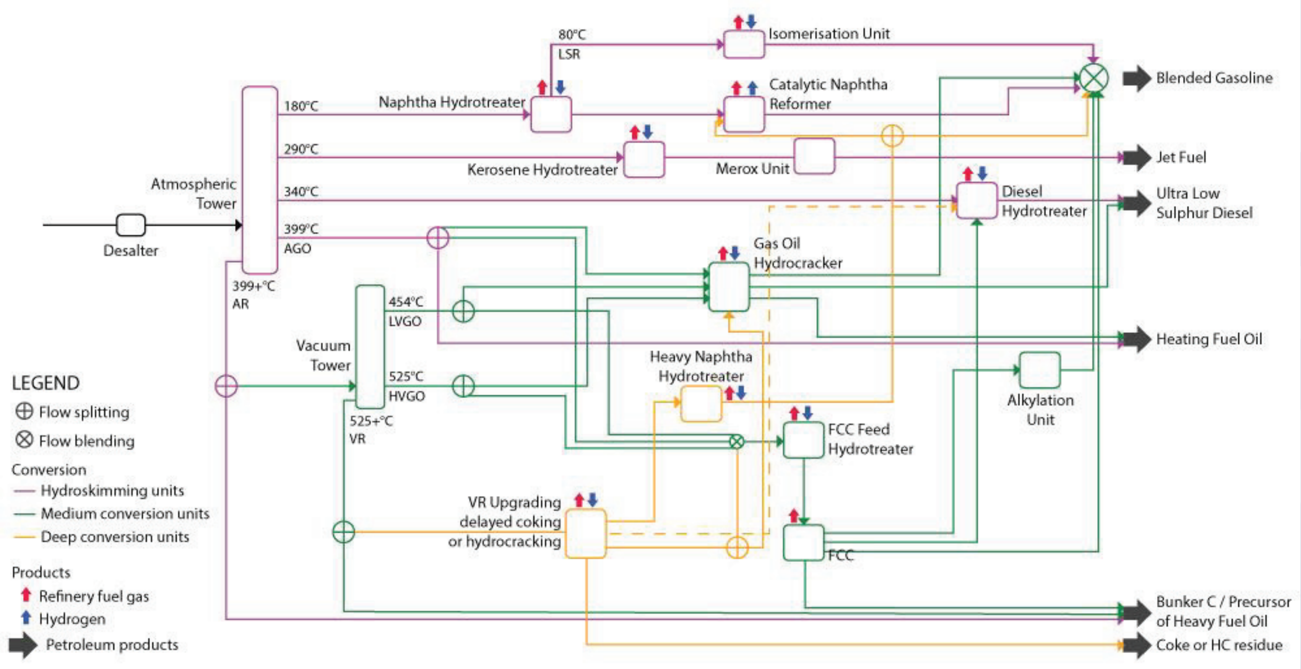
2.1. STAGES AND CONFIGURATIONS IN MIDSTREAM EMISSION REPORTING

Refining is the process of "breaking crude oil down into its various components, which are then selectively reconfigured into new products" (U.S. Energy Information Administration 2020b). As mentioned in Section 2.2, the midstream refining sector can be divided into three basic steps (U.S. Energy Information Administration 2020b): separation, conversion, and treatment.

Figure 5 shows the simplified process flow from crude oil to refined products through the three stages.

A refinery configuration represents a combination of equipment to process a particular blend of crude oil into certain types and amounts of products. The three default refinery configurations in the PRELIM model are based on API gravity and sulfur content:

FIGURE 5: PRELIM SIMPLIFIED PROCESS FLOW



Source: *Abella, Motazedi, and Bergerson (2020).*

TABLE 7: REFINERY CONFIGURATIONS AND CRUDE TYPES

SULFUR CONTENT	API GRAVITY		
	22	22-32	> 32
≤ 0.5%	Deep conversion (Heavy Crude)	Medium conversion (Medium Sweet Crude)	Hydroskimming (Light Sweet Crude)
> 0.5%	Deep conversion (Heavy Crude)	Medium conversion (Medium Sour Crude)	Medium conversion (Light Sour Crude)

Emissions from the refinery process can be divided into five sources (Gordon, et al. 2015):

1. Fluid Catalytic Cracking (FCC) Catalyst Regeneration: cracking heavy crude oils into gasoline and other lighter products (Gary et al. 2001).
2. Hydrogen via Steam Methane Reformer: producing H_2 and CO by chemical reaction of hydrocarbons and H_2O (Liu, Song, and Subramani 2010).
3. Steam: energy used in producing steam of gases during the refining process.
4. Water: energy used in injecting water during the refining process.
5. Heat: energy used in producing heat during the refining process.

Fugitive emissions are less than 10% of the emissions from energy used in the refining process, so they are not included in the PRELIM calculation (Abella, Motazedi, and Bergerson 2020).

2.2. KEY PARAMETERS

API gravity and sulfur content are both significant determining factors of total midstream refinery emission factors, which in turn confirms the significance level of crude type for these emission factors, since the crude type is determined by these two factors. The crude type affects the process units and energy requirement employed in the refinery, which lead to emissions. In addition, the energy used in producing grey hydrogen for processing crude is the main driver of refinery energy used and GHG emissions; the amount of hydrogen is also determined by the quality of the crude. Lighter crudes yield more hydrogen when refined and thus require less hydrogen inputs during refining (Gordon et al. 2015).

2.3. ESTIMATION OF COUNTRY-SPECIFIC EMISSION FACTORS

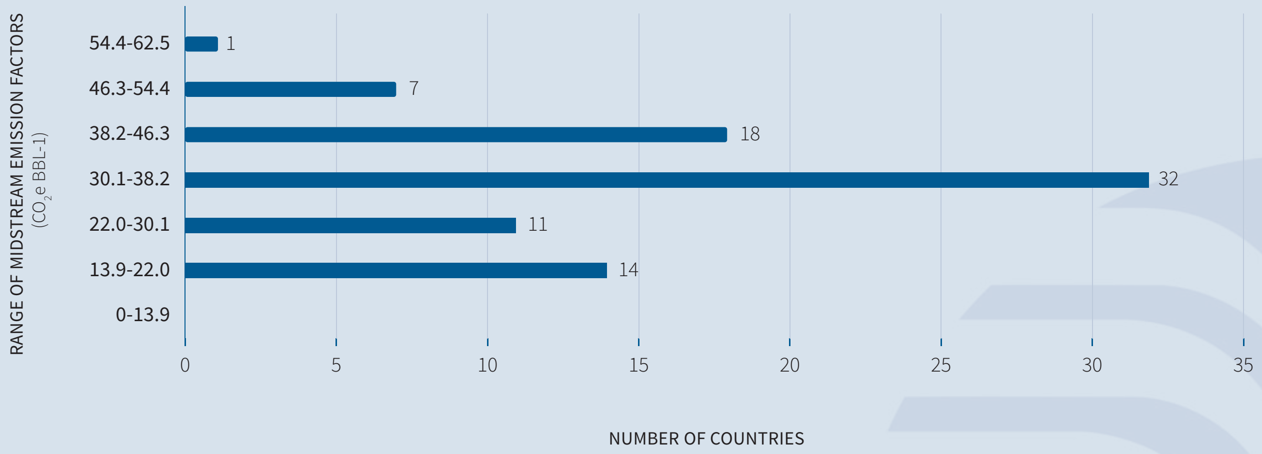
Like in the upstream sector, various factors influence the level of emissions at each stage of the midstream sector, and we estimate country-specific emission factors to simplify them and focus on the most influential ones. We obtain the country-specific emission factors from refining directly from the same dataset used in estimating upstream emission factors since the dataset already contains the emission factors of each refining configuration (hydroskimming, medium conversion, and deep conversion) for 83 destination countries in the PRELIM model. The modeled midstream emission factors are based on the default values of refining configuration in PRELIM and are under the 100-year AR5 Global Warming Potential (GWP) setting.[19] To derive the country-specific midstream emission factors, we take the average of the emission factors weighted on refining volume. Appendix 4 shows the full list of the estimated midstream emission factors for all 83 countries.

TABLE 8: EFFECT OF KEY PARAMETERS ON MIDSTREAM EMISSION FACTORS

	ELECTRICITY	HEAT	STEAM	HYDROGEN VIA SMR	FLUID CATALYTIC CRACKING REGENERATION	TOTAL REFINERY EMISSION FACTORS
SULFUR	0.0718 (0.0802)	-0.2761 (0.3044)	0.1299 (0.0989)	1.2889 (0.9708)	0.4086 (0.1838) *	1.6232 (1.5693)
CRUDE OIL API	-0.0641 (0.0169) *	-0.0986 (0.0948)	-0.0869 (0.0200) *	-0.9643 (0.2058) *	-0.1487 (0.0244) *	-1.3626 (0.3579) *
CRUDE OIL TYPE	1.2720 (0.1333) *	3.9588 (0.7111) *	1.6738 (0.1399) *	16.2605 (1.7398) *	2.8378 (0.0929) *	26.0029 (2.6198) *

This table reports coefficients from univariate regression of electricity, heat, steam, hydrogen, FCC, and total refinery emission factors on key inputs in the PRELIM Model. The sample includes 71 global oil fields data used in OCI (Gordon et al. 2015). Standard errors are reported in parentheses. * after coefficients denotes significance at the 5% level.

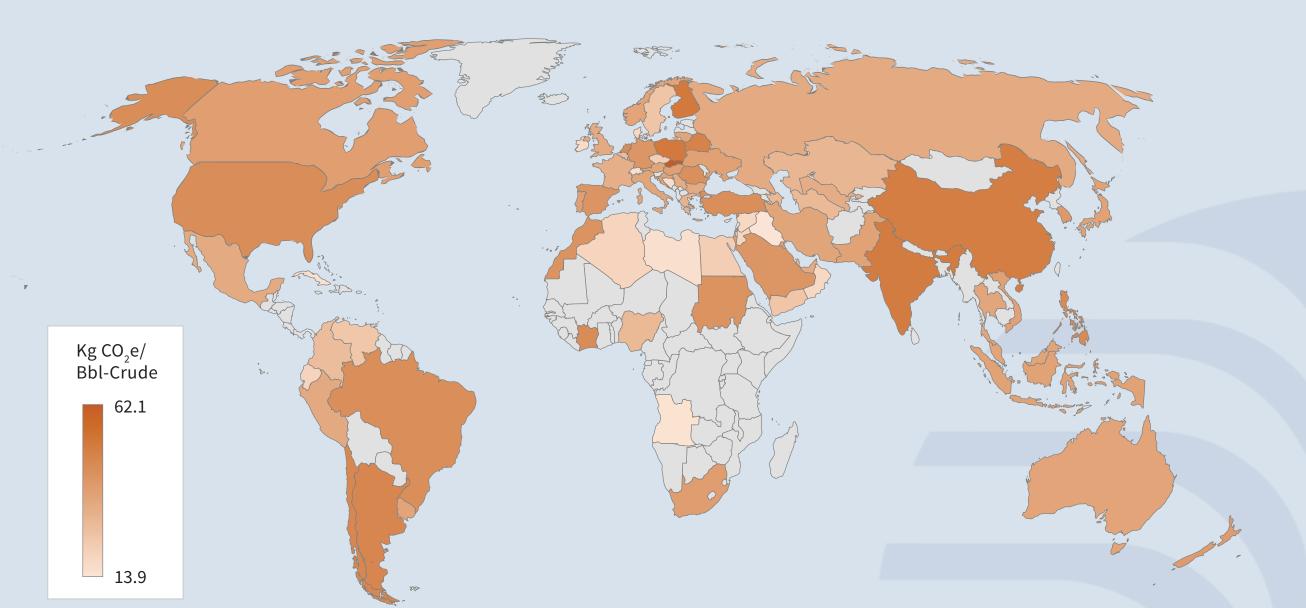
FIGURE 6: HISTOGRAM OF MIDSTREAM EMISSION FACTORS FOR 83 DESTINATION COUNTRIES



FOOTNOTE

[19] GWP refers to the “total contribution to global warming resulting from the emission of one unit of the gas relative to one unit of CO_2.” The 100-year AR5 are the most recent GWP values from the IPCC Fifth Assessment Report (Dahe and Stocker 2014) in a 100-year time horizon. The default emission factors are calculated by converting other gases to CO_2 equivalent using the 100-year AR5 GWP factors.

FIGURE 7: MIDSTREAM EMISSION FACTORS BY COUNTRY IN 2015



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2.4. CHANGE OF COUNTRY-SPECIFIC EMISSION FACTORS OVER TIME

Refining processes and equipment have changed over the years to respond to environmental regulations. Using statistically significant determining factors of midstream emissions, we made some adjustments to our estimates to reflect those changes. The regression analysis in Section 4.2 reveals that API gravity and sulfur content are the significant determining factors of midstream emission factors. In Table 9 we assess the feasibility of using API gravity and sulfur content to estimate the time-series change in midstream emission factors by running a multivariate regression. The result of our statistical analysis shows that API gravity and sulfur content explain 40.6% of the variation in refining emission factors.

Our empirical results show that the average API gravity for the crude oil used by the U.S. refining industry has gradually decreased until the mid-2000s and then bounced back, while the average sulfur content of crude oil increased from 1985 to 2000 and stabilized since the early 2000s. The bounce-back of API gravities is primarily related to the increase of light crude oil produced from low-permeability formations (U.S. Energy Information Administration 2017).

TABLE 9: MULTIVARIATE REGRESSION ON REFINING EMISSION FACTORS

	REFINING EMISSIONS
Sulfur Content	-2.7381 (1.651)
API Gravity	-1.5085 (0.224)*
N	71
R^2	40.60%
Correlation between Sulfur and API	-0.39

Note: *This table reports coefficients from* ***multivariate*** *regression of total refining emission factors on sulfur content and API gravity. The sample (N) includes 71 global oil fields data used in OCI (Gordon 2015). Standard errors are reported in parentheses. * after coefficients denotes significance at the 1% level. The coefficient of sulfur content under multivariate regression is negative, which is different from that under univariate regression. Even if sulfur content is not statistically significant, including sulfur content increases R2* [20] *from 38.2% to 40.6% and decreases Akaike information criterion (AIC)*[21] *from 605.3 to 604.5, which indicates the multivariate regression by sulfur content and API gravity fits better than the univariate regression by API gravity.*

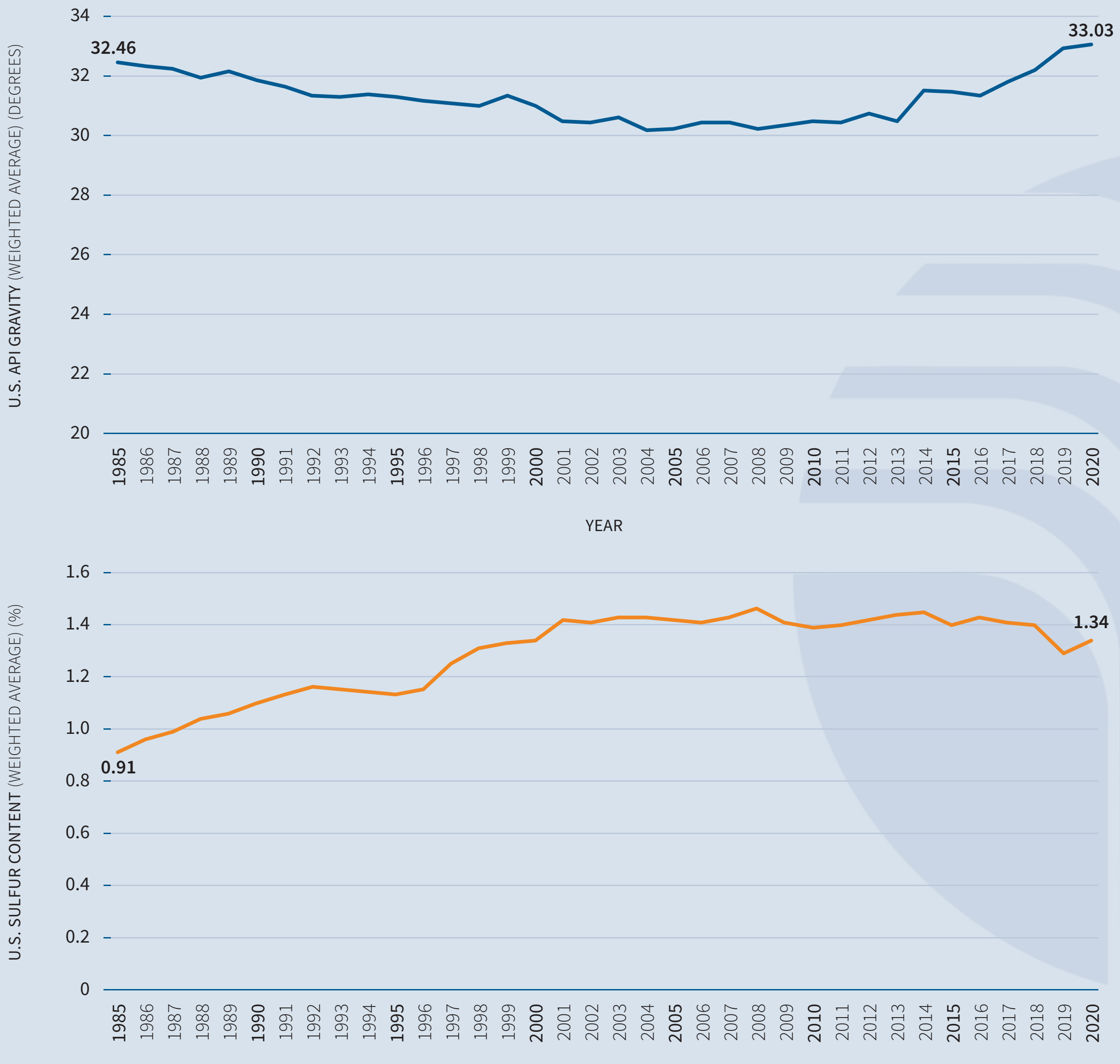
FOOTNOTES

[20] Measure of the proportion of the variance for a dependent variable that is explained by independent variables in a regression model (Carpenter 1960).

[21] Measure of the prediction error and the relative quality of statistical models for a given set of data (McElreath 2018).

To derive the time-series change in midstream emission factors due to the change in API gravity and sulfur content, we first linearly regress U.S. midstream emission factors on API gravity and sulfur content to obtain their coefficients. Then we apply the coefficients to U.S. historical data on API gravity and sulfur content to derive a time series of midstream emission factors for the United States. To address the lack of publicly available data, and acknowledging that U.S. refinery throughput accounts for the largest share (21.3%) of global refinery throughput from 1980 to 2019, we apply the same percentage of change to other countries' midstream emission factors, though recognizing that this does not reflect the reality accurately.

FIGURE 8: HISTORICAL U.S. REFINING INDUSTRY AVERAGE API GRAVITY AND SULFUR CONTENT



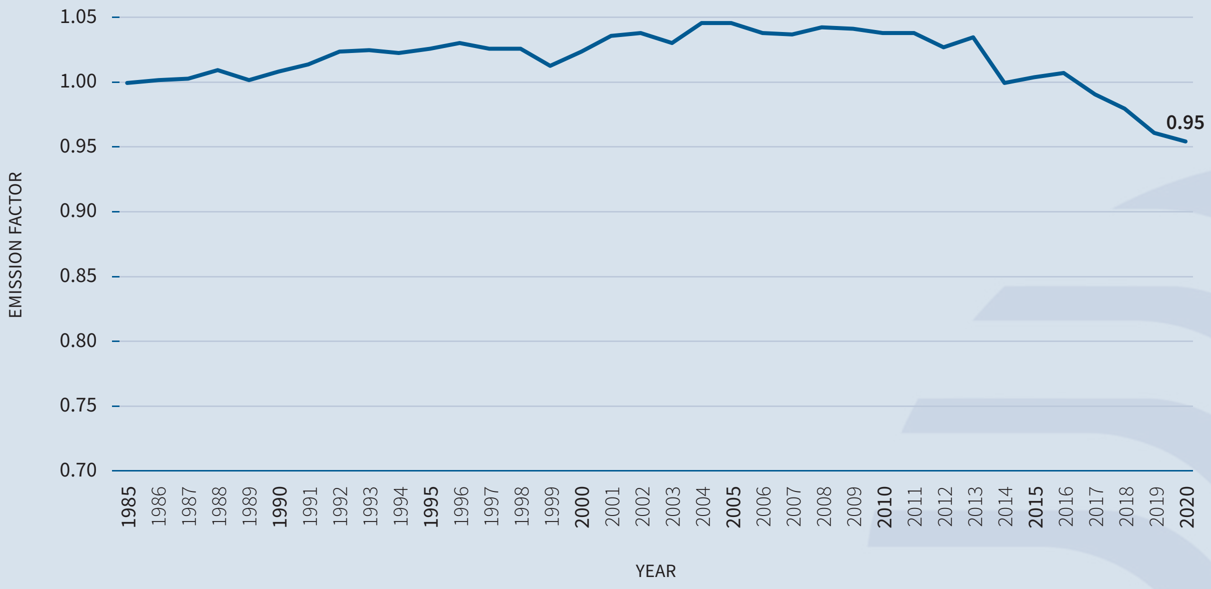
Source: *U.S. Energy Information Administration.*

We normalize the U.S. midstream emission factor in 1985 as 1 and apply the yearly change rates of U.S. midstream emission factors to our estimated country-specific emission factors in 2015 to derive the time-series emission factors for the 83 destination countries in our dataset from 1985 to 2020. Given the lack of API gravity and sulfur content data from 1980 to 1984, we apply the 35-year rolling average change rate to estimate the time-series emission factors from 1980 to 1984.

Appendix 4 shows the full time-series of estimated midstream emission factors for all 83 countries.

The estimated midstream emission factors increased over time before 2004 due to the decrease of API gravity (heavier oil) and the increase of sulfur content, but the increasing trend reverted afterward due to the bounce-back of API gravity (lighter oil).

FIGURE 9: CHANGE OF NORMALIZED MIDSTREAM EMISSION FACTORS OVER TIME



PART 3

DOWNSTREAM SECTOR

3.1. DOWNSTREAM STAGES AND EMISSIONS CALCULATION

Emissions in the downstream sector include emissions from transport and combustion. Transport emissions occur in transporting petroleum products (gasoline, diesel, jet fuel, fuel oil, residual fuel, and liquefied petroleum gas (LPG)) from the refineries to domestic and global petroleum products sales markets. Combustion emissions occur during the use of petroleum products in the end market. We used the OPEM model to calculate transport and combustion emissions (Gordon 2016).

Transport emissions are calculated by:

$$\text{Transport emissions} = \sum_{i=1}^{N}\sum_{t=1}^{T}\sum_{l=1}^{L} \text{Distance}_l \times \text{Transport emission factor}_{it} \times \text{Volume}_t$$

i: Transport mode.
t: Fuel type.
l: Transport route.

Three factors determine transport emissions: distance, volume, and transport emission factors, depending on both the fuel type and the transport mode. For example, shipping 1 metric ton of fuel for 1 km using tanker trucks will release 0.09 kg CO_2e; by rail, 0.02 kg CO_2e; and using pipelines, 0.01 kg CO_2e (Gordon 2016). Shipping larger volumes over longer distances also increases emissions.

Transport emissions are calculated by:

$$\text{Combustion emissions} = \sum_{i=1}^{N} \text{Volume weight} \times \text{Combustion emission factor}_i$$

i: Fuel type.

The quantity of fuels entering petroleum products sales markets, the percentage of fuels that are combusted ultimately, and the combustion emission factors of different fuel types determine combustion emissions.

3.2. ESTIMATION OF COUNTRY-SPECIFIC EMISSION FACTORS

We follow the calculation formulas in the OPEM model to estimate the country-specific emission factors for the downstream sector.

For the transport distance using pipelines and trucks, short of better data, we apply the default transport distance used in the OPEM model (Gordon 2016) and in OCI (Gordon et al. 2015): the default distances are estimated by the typical route transported by tanker truck, which is 380 km from Houston to the Boston region, and by pipeline, which is 2414 km from Houston to the New York–New Jersey region. We apply the default distances to all countries, though recognizing that this does not reflect the reality of global trade routes of crude oil by road or pipeline. For the maritime routes, we apply the empirical results in Greene, Jia, and Rubio-Domingo's (2020) work about maritime transportation of crude oil to derive the average transport distance by ocean tanker for each region, assuming the transportation of petroleum products via ocean tanker will follow the same maritime routes. In general, "the routes and distances different products take from the refinery to the market are highly variable and largely opaque." (Gordon et al. 2015) For this reason, these results are shrouded in high uncertainty.

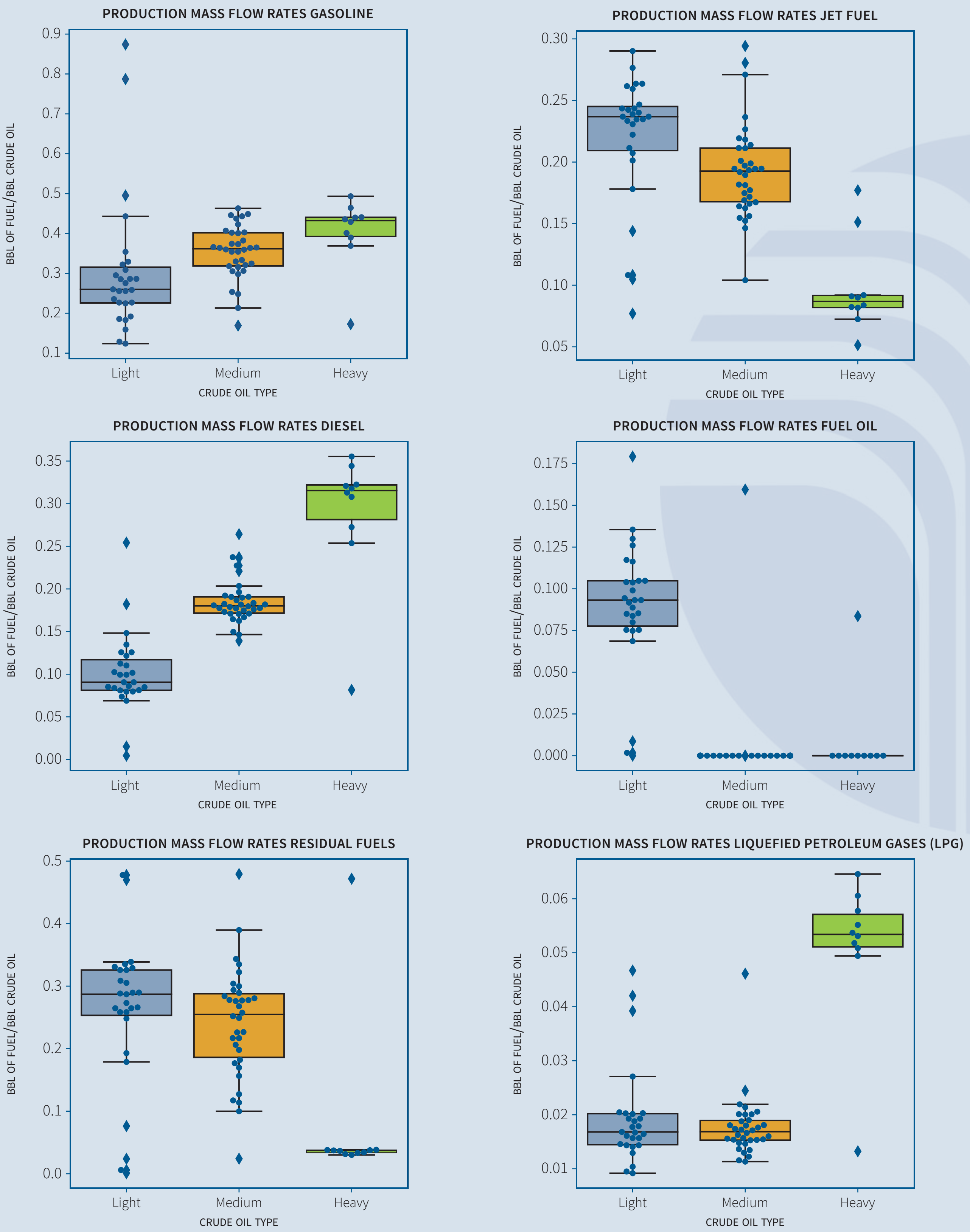
We apply the default transport emission factors by mode and fuel used in the OPEM model, which originates from GREET (Cai, Sykora, and Wang 2021).

For the volume factor, we assess production mass flow rates for each fuel (quantity of fuel product produced per kilogram of crude oil). To this end, we use the PRELIM model since the volume of refinery products is equivalent to the volume of

TABLE 10: FRAMEWORK OF OPEM MODEL

TRANSPORT (MODE OF TRANSPORT)	**TRANSPORT FUEL**	**EMISSION FACTOR** (g CO_2e/kgkm)	**DISTANCE TRAVELED (KM)**	**TRANSPORT EMISSIONS** (Kg CO_2e/bbl of crude)
Pipeline Emissions				
Heavy-Duty Truck Emissions				
Ocean Tanker Emissions				
COMBUSTION	**COMBUSTION EMISSION FACTORS**	**EMISSION FACTOR UNITS**	**% COMBUSTED**	**TOTAL COMBUSTION EMISSIONS** (Kg CO_2e/bbl of crude)
Gasoline				
Jet Fuel				
Diesel				
Fuel Oil				
Residual fuels				
Liquefied Petroleum Gases(LPG)				

FIGURE 10: PRODUCTION MASS FLOW RATES FOR DIFFERENT FUEL TYPES BY CRUDE OIL TYPE



PRODUCTION MASS FLOW RATES GASOLINE

PRODUCTION MASS FLOW RATES JET FUEL

PRODUCTION MASS FLOW RATES DIESEL

PRODUCTION MASS FLOW RATES FUEL OIL

PRODUCTION MASS FLOW RATES RESIDUAL FUELS

PRODUCTION MASS FLOW RATES LIQUEFIED PETROLEUM GASES (LPG) products transported. In addition, since the type of crude oil determines the refinery configuration used in the PRELIM model, thus leading to different production mass flow rates, we use the machine learning model to estimate production mass flow rates for fuels of different types of crude oil. We apply the machine learning model to the OCI dataset, learning the relationship between production mass flow rates for each fuel product with the crude oil type. Then we assign the estimated production mass flow rates to the 83 countries based on the crude oil type (see Figure 10 on the previous page).

The predicted production mass flow rates show an inverse relationship between the lightness of the crude type and the lightness of the fuel product. Predicted production mass flow rates for jet fuel, residual oil, and fuel oil are higher in refineries of light crude oil, while rates for gasoline, diesel, and LPG are higher in refineries of heavy crude oil. This result is due to the composition of the sample but also due to the adoption of deep conversion refinery configuration in refineries of heavy crude oil. Besides catalytic cracking and hydrocracking to convert gas oil fraction into simpler molecules, the deep conversion also includes coking units, which further break down residual oil fraction into lighter streams and produce more light products such as LPG, gasoline, and diesel. As a result, deep conversion refineries with sufficient coking capacity minimize the residual oil in their product slates. On the contrary, refineries utilizing hydroskimming or medium conversion configuration have no capacity for converting all residual oil fraction and will still produce some heavy, low-value products like residual fuel and fuel oil (Math Pro 2011). Within the OCI dataset that has both crude oil type and refinery configuration, we observed a significant correlation between the two variables, which confirmed the data trend in Figure 10.

TABLE 11: REFINERY CONFIGURATION AND CRUDE OIL TYPE OF OCI DATASET

	LIGHT	MEDIUM	HEAVY
Hydroskimming	27	0	0
Medium conversion	0	34	0
Deep conversion	0	2	8

Multiplying the three estimated components, we derive the transport emission factors for each refinery type and region. We then assign the estimated emission factors to the destination countries based on crude oil type and region.

For combustion emission factors, we also apply the default emission factors by fuel used in the OPEM model, which originates from GREET (Cai, Sykora, and Wang 2021). Then we multiply the estimated production mass flow rate (assessed above) and these default emission factors to derive the combustion emission factors per type of crude oil.

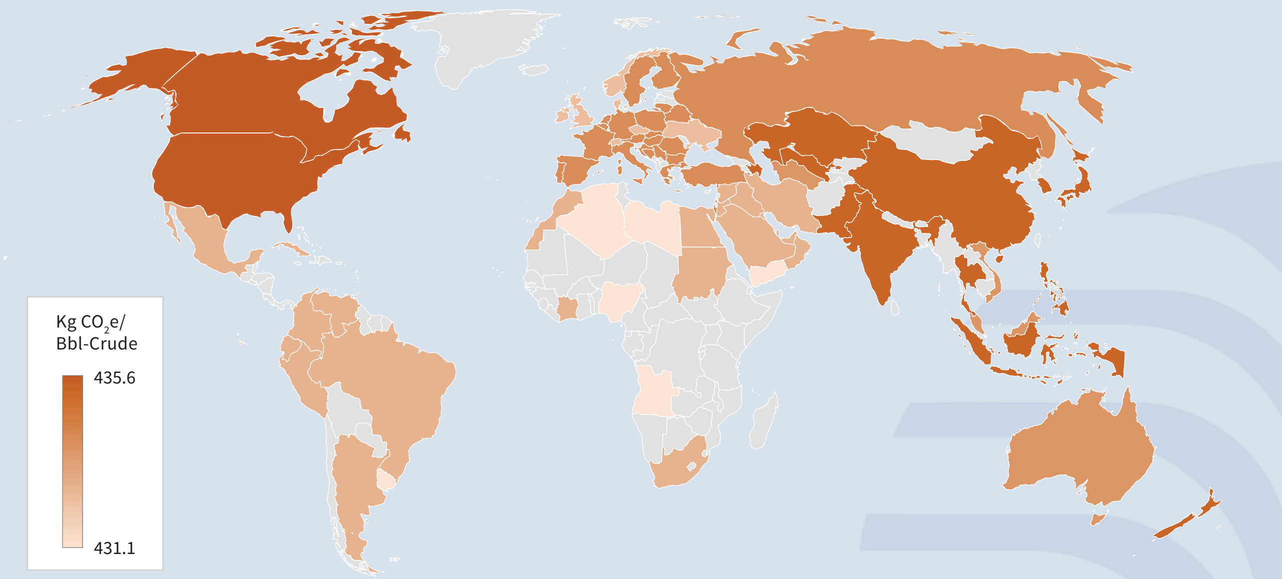
TABLE 12: ESTIMATED TRANSPORT EMISSIONS FOR CRUDE OIL TYPE AND REGION

TRANSPORTATION EMISSION FACTORS (Kg CO_2e bbl-1)		AFRICA	ASIA & PACIFIC	EUROPE	MIDDLE EAST	NORTH AMERICA	SOUTH/LATIN AMERICA
CRUDE OIL TYPE	Light	11.29	13.83	12.54	11.29	14.13	11.29
	Medium	11.35	13.89	12.60	11.35	14.20	11.35
	Heavy	10.65	13.03	11.83	10.65	13.32	10.65

TABLE 13: ESTIMATED COMBUSTION EMISSIONS FOR CRUDE OIL TYPE

CRUDE OIL TYPE	COMBUSTION EMISSION FACTORS (Kg CO_2e bbl-1)							
	Gasoline	Jet Fuel	Diesel	Fuel Oil	Coke	Residual fuels	LPG	Total
Light	111.95	92.06	40.24	41.60	0.00	129.51	4.48	419.84
Medium	139.65	79.88	85.29	0.00	0.01	111.77	4.80	421.40
Heavy	182.18	38.91	147.77	0.00	0.36	18.13	15.28	402.64

FIGURE 11: DOWNSTREAM EMISSION FACTORS BY COUNTRY IN 2015



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3.3. CHANGE IN COUNTRY-SPECIFIC EMISSION FACTORS OVER TIME

3.3.1. Change in Transportation Emission Factors Over Time

The default transport emission factors used in the OPEM model originate from the emission factors in the GREET model. Like the default emission factors used in the OPGEE model, the default emission factors by transportation mode and fuel type change over time due to the development of transportation. Using the GREET model, we simulate the evolution of transportation technology and then apply the trend to simulate the time series of default transport emission factors from 1990 to 2020 (Cai, Sykora, and Wang 2021). Based on inputs from the GREET model and OPEM's calculation model, while the emission factors for other transport modes remain stable, the emission factor for heavy-duty trucks decreased 22.38%, from 0.1050 g CO_2e/kgkm in 1990 to 0.0815 g CO_2e/kgkm in 2020 (Cai, Sykora, and Wang 2021). This finding is consistent with government policies aiming at reducing emissions from trucks over time.[22]

TABLE 14: TRANSPORT EMISSION FACTORS BY TRANSPORTATION MODE OVER TIME

EMISSION FACTORS (g CO_2e/kgkm)	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
TRUCK	0.1050	0.0954	0.0939	0.0895	0.0905	0.0888	0.0815
BARGE	0.0414	0.0414	0.0415	0.0415	0.0415	0.0415	0.0415
PIPELINE	0.0190	0.0190	0.0190	0.0190	0.0190	0.0190	0.0190
RAIL	0.0294	0.0294	0.0294	0.0294	0.0295	0.0295	0.0296
OCEAN TANKER	0.0046	0.0046	0.0047	0.0047	0.0047	0.0047	0.0047

Source: *Prepared by the authors based on original parameters from the GREET model and the calculation model from the OPEM model.*

FOOTNOTES

[22] For instance, in the United States, the EPA and the National Highway Traffic Safety Administration (NHSTA) issued GHG emissions regulation for heavy-duty trucks in 2011 and further rolled out new regulations in 2016 to cover a wider range of heavy-duty trucks and the accelerated innovation in clean vehicles (U.S. Environmental Protection Agency 2017).

TABLE 15: TIME SERIES OF TRANSPORTATION EMISSION FACTORS BY REGION AND CRUDE OIL TYPE

TRANSPORTATION EMISSION FACTORS (Kg CO$_2$e bbl-1)		**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**
AFRICA	Light	12.05	11.57	11.50	11.27	11.32	11.29	10.87
	Medium	12.11	11.63	11.55	11.33	11.38	11.35	10.92
	Heavy	11.36	10.91	10.84	10.63	10.68	10.65	10.25
ASIA & PACIFIC	Light	14.57	14.09	14.03	13.81	13.86	13.83	13.41
	Medium	14.64	14.16	14.10	13.88	13.93	13.89	13.47
	Heavy	13.74	13.29	13.23	13.02	13.07	13.03	12.64
EUROPE	Light	13.30	12.82	12.75	12.53	12.58	12.54	12.12
	Medium	13.36	12.88	12.81	12.59	12.64	12.60	12.18
	Heavy	12.54	12.08	12.02	11.81	11.86	11.83	11.43
MIDDLE EAST	Light	12.05	11.57	11.50	11.27	11.32	11.29	10.87
	Medium	12.11	11.63	11.55	11.33	11.38	11.35	10.92
	Heavy	11.36	10.91	10.84	10.63	10.68	10.65	10.25
NORTH AMERICA	Light	14.87	14.39	14.33	14.11	14.16	14.13	13.71
	Medium	14.95	14.46	14.40	14.18	14.23	14.20	13.77
	Heavy	14.02	13.57	13.51	13.30	13.35	13.32	12.92
SOUTH/LATIN AMERICA	Light	12.05	11.57	11.50	11.27	11.32	11.29	10.87
	Medium	12.11	11.63	11.55	11.33	11.38	11.35	10.92
	Heavy	11.36	10.91	10.84	10.63	10.68	10.65	10.25

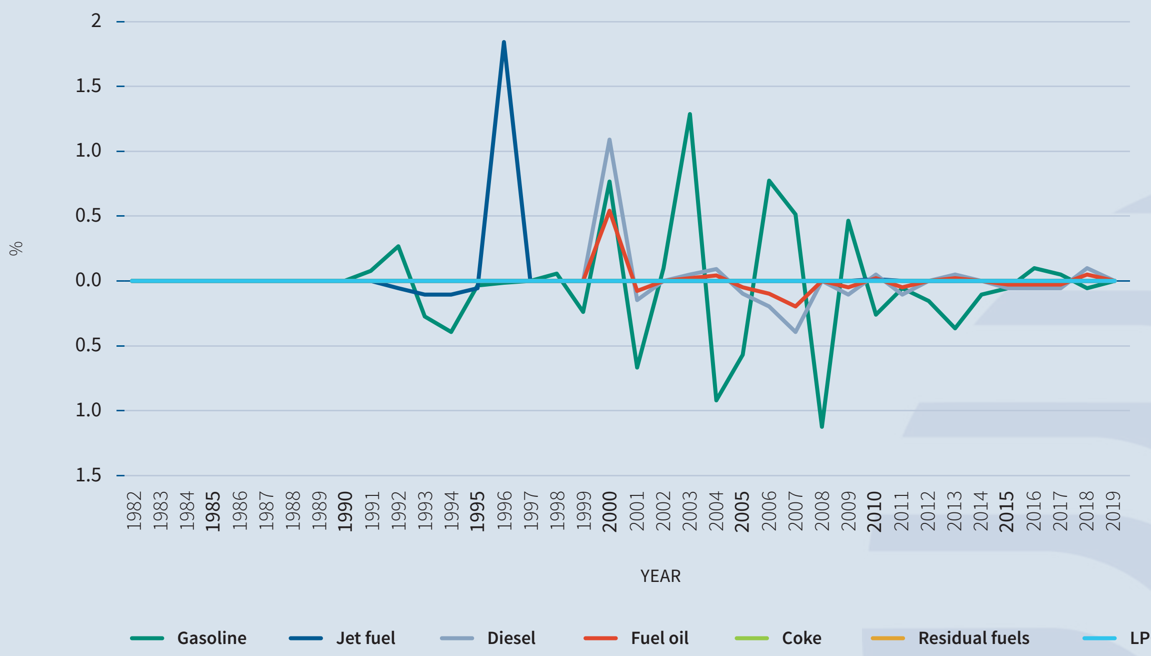
To assess the effect of the change in default emission factors over time on transport emission factors, we apply the time-series data of default emission factors from the GREET model to the OPEM model to recalculate the transportation emission factors for each time period. Table 15 presents the results. In general, the transportation emission factors are estimated to decrease over time since the decrease of emission factors of truck transport dominates the trend.

3.3.2. Change in Combustion Emission Factors Over Time

We assess the time-series change in combustion emission factors based on EIA's database of CO$_2$ Emissions Coefficients for petroleum products from 1980 to 2019. The results presented in Table 16 reveal that the average year-on-year changes of combustion emission factors are less than 0.05% for all petroleum products. Thus, we disregard the time-series change of combustion emission factors in our model.

The full time series of country-specific downstream emission factors is in Appendix 5.

TABLE 16: YEAR-ON-YEAR PERCENTAGE CHANGE OF COMBUSTION EMISSION FACTORS



YOY % OF CHANGE	GASOLINE	JET FUEL	DIESEL	FUEL OIL	COKE	RESIDUAL FUELS	LPG
Average	-0.02%	0.04%	0.01%	0.00%	0.00%	0.00%	0.00%

Source: *Cai, Sykora, and Wang (2021).*

3.4. LIFE-CYCLE EMISSION FACTORS

Summing up emission factors at all stages, we create a time series of life-cycle emission factors from 1980 to 2019 for 83 countries (see Appendix 6). Life-cycle emission factors vary by country due to the variance in crude oil grades, refinery configuration, and transportation. Figure 12 shows the life-cycle emission factors by country in 2015, ranging from Denmark's 469.55 kg CO_2e/bblCrude to Uzbekistan's 624.13 kg CO_2e/bblCrude. The emission factors also vary over time due to technological evolution, and the aging and replacement ratio of oil fields.

The downstream sector accounts for the largest share of life-cycle emission factors, which is 85.91% on average over time, while the midstream sector accounts for 7.95% and the upstream sector, for 6.22%. Our estimated data is similar to that of the OCI dataset, which is 83.81% for OPEM downstream emission factors, 10.78% for OPGEE upstream emission factors, and 5.41% for PRELIM midstream emission factors.[23] (Gordon et al. 2015).

FOOTNOTES

[23] We calculate the average percentage of each sector emission factors in the OCI dataset, weighting by production volume of 75 oil fields in "Oil Climate Index Webtool - Phase II" dataset. (Gordon, et al. 2015)

FIGURE 12: LIFE-CYCLE EMISSION FACTORS BY COUNTRY IN 2015

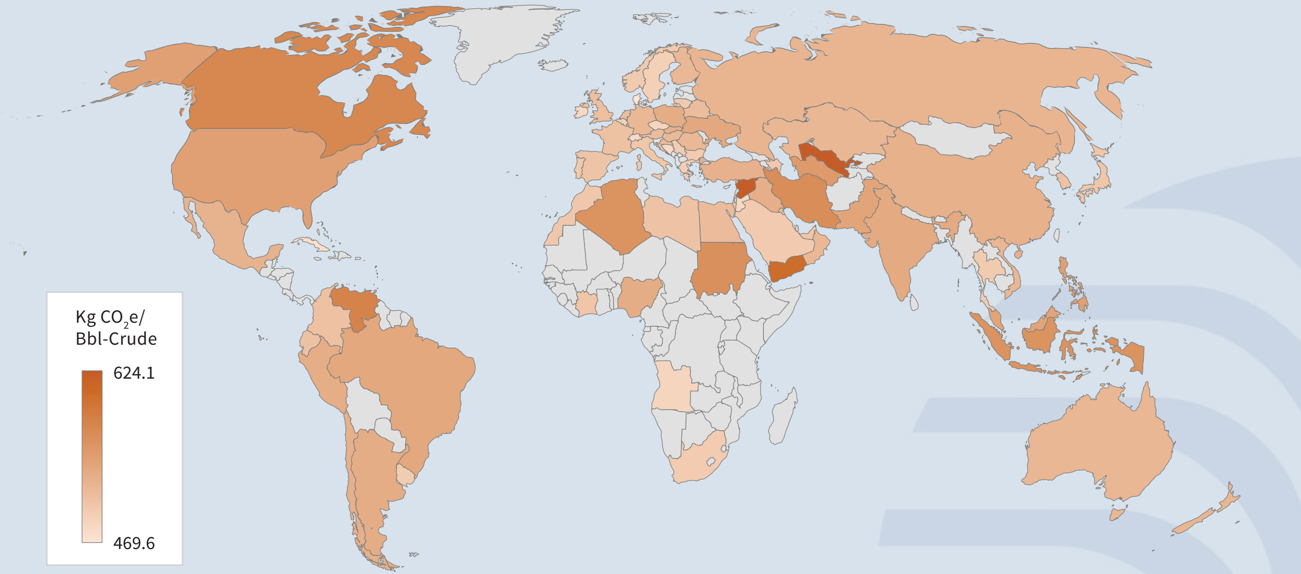


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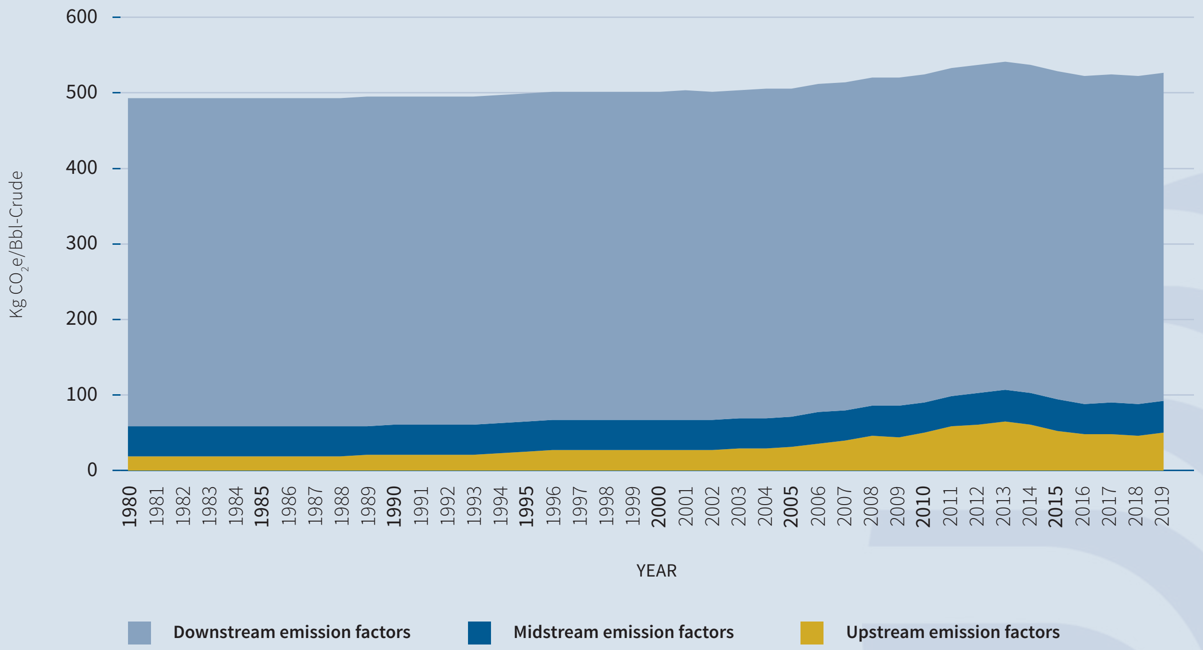
FIGURE 13: LIFE-CYCLE EMISSION FACTORS BY SECTORS WEIGHTED AVERAGE BY OIL CONSUMPTION



PART 4

CARBON FOOTPRINT OF THE PETROLEUM PRODUCTS SALES SECTOR AND THE OIL REFINING SECTOR

4.1. CARBON FOOTPRINT OF THE PETROLEUM PRODUCTS SALES SECTOR

The carbon footprint of the petroleum products sales sector (LPG, gasoline, jet fuel, kerosene, fuel oil, and residual oil) accounts for the CO_2 released during the sales operation as well as along the value chain of crude oil, which is referred to as the sum of scope 1, 2, and 3 emissions (Hertwich and Wood 2018). The sector is the final link in the oil value chain and the bridge connecting it to the end-users and, as such, has a crucial impact on the emissions from petroleum products. Global consumption of petroleum products is the source of combustion emissions, the largest share of life-cycle GHG emissions from oil.

Applying a life-cycle assessment, we trace the carbon footprint of petroleum products sold based on the destination country or region and the year of the sale, considering all associated emissions along the value chain and the variety of the refined products in terms of crude oil type, oil fields, refinery configuration, and transport. By assessing the carbon footprint of the sector, we quantify its share in GHG emissions as well as the GHG emissions from the combustion of petroleum products.[24]

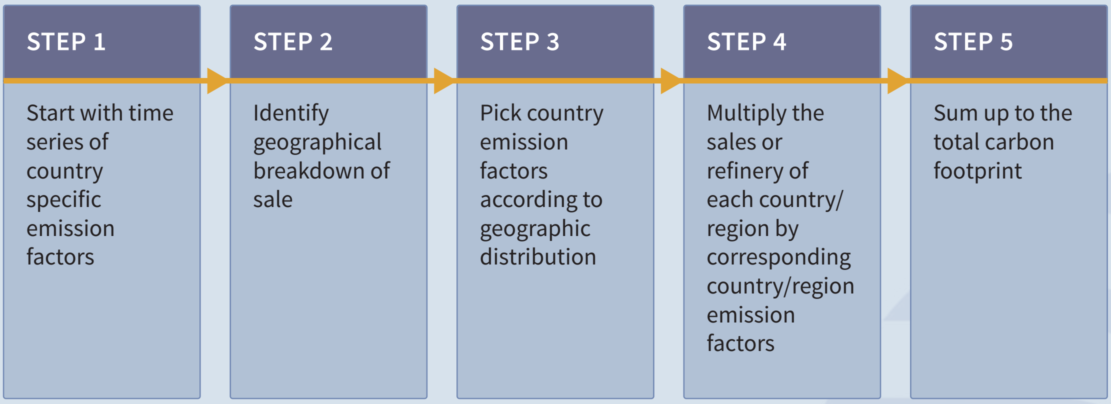
Also, we incorporate the fact that some petroleum products are consumed but not combusted. They are used as construction materials, chemical feedstocks, lubricants, solvents, waxes, and other products (U.S. Energy Information Administration 2018). According to the literature, non-combusted petroleum products accounted for 13% of total petroleum products consumption in the United States in 2017 (U.S. Energy Information Administration 2018) and 13.9% in European Union (EU) in 2019 (Eurostat 2021). Hence, we apply a 13.45% discount rate, which is an average of U.S. and EU non-combusted petroleum products consumption proportion, to the combustion emissions within the life-cycle carbon footprints for both the petroleum product sales sector and the refining sector.[25]

The petroleum products sales sector is highly concentrated. According to the data we collected, sales of petroleum products by the six supermajors account for 24.15% of global petroleum consumption.[26] By quantifying the supermajors' life-cycle carbon footprint in the sector, we focus on the major contributors to GHG emissions in the industry and determine their weights in the sector in terms of GHG emissions.

We first summarize the supermajors' sales data (volume of petroleum products sold in their wholesale and retail segments as reported in company financial reports, adjusting for the merger and acquisition [M&A] effect[247]) and the geographic distribution of their sales (based on revenues of volumes depending on the available data in annual reports). We estimate the companies' carbon footprint by our life-cycle model to the data (see Figure 14).

Large companies in the sector, including the six supermajors, have recently started to report their estimated scope 3 emissions. Even though we haven't adopted a scope-based approach, we compare the carbon footprint estimated under our model with the scope 1, 2, and 3 emissions reported by the companies, assess the boundaries of emissions reporting by different companies, and evaluate the completeness of their emissions reporting.

FIGURE 14: METHODOLOGICAL APPROACH TO ASSESS THE COMPANIES' CARBON FOOTPRINT



FOOTNOTES

[24] We assume that all petroleum products are combusted.

[25] We did not take into account that some variable fractions of plastics, tires, lubricants, waxes, and other non-energy products are actually combusted in post-consumer use.

[26] The data sources include: global consumption of petroleum products from 1980 to 2019 (U.S. Energy Information Administration 2021a); companies' crude oil production from 1980 to 2018 (Climate Accountability Institute 2020); BP volume of sales of petroleum products from 2008 to 2019 (Bloomberg LP 2021a); geographic distribution of BP's revenue (Bloomberg LP 2021a); Chevron supplementary annual reports (Chevron 2011; Chevron 2016; Chevron 2020; Chevron 2021); companies' petroleum products production data from Refinery Report in Oil & Gas Journal (2019); Eni fact books (Eni 2012; Eni 2015; Eni 2018; Eni 2020a; Eni 2020b; Eni 2021); ExxonMobil Financial & Operating Review (ExxonMobil 2005; ExxonMobil 2010; ExxonMobil 2014; ExxonMobil 2018; ExxonMobil 2021a; ExxonMobil 2021b; ExxonMobil 2021c; ExxonMobil 2021d); ExxonMobil's petroleum products sales segment by destination country for 2000–2019 (Bloomberg LP 2021b); Shell investors' handbook (Shell 2012; Shell 2015; Shell 2020); TotalEnergies fact books (TotalEnergies 2007; TotalEnergies 2010; TotalEnergies 2015; TotalEnergies 2020b); BP statistics (2020); companies' refining capacity in 2020 from McKinsey Refinery Capacity Database (Fitzgibbon 2020).

[27] We adjusted for the M&A effect between oil companies, adding time-series data of acquired companies to the merged companies.

4.1.1. Boundaries

Table 17 matches the stages of the value chain that this study covers to assess the petroleum products sales sector's carbon footprint with the scopes and scope 3 categories defined by IPIECA of the scope and boundary of emissions from the petroleum products sales sector. According to IPIECA's definitions, the carbon footprint of the petroleum products sales sector does not only include scopes 1 and 2 emissions from transporting petroleum products from refinery to retail and wholesale market but also scope 3 emissions, which include upstream and midstream emissions of the products sold and the emissions from the use of the petroleum products (IPIECA 2011).

4.1.2. Global Footprint

To quantify the carbon footprint of the global petroleum products sales sector, we use data on the global consumption of petroleum products from 1980 to 2019 (U.S. Energy Information Administration 2021a). On average, throughout the period, the world consumed 77.26 million barrels of petroleum products per day; the United States, China, Japan, Germany, and India were the largest consumers (see Figure 15).

We multiply the countries' consumption by the corresponding country-specific life-cycle emission factors in our model to estimate the carbon footprints of the sector by country. For countries not included in our model, we apply the global average emission factors, though we acknowledge this results in a simplification. Consolidating all countries' carbon footprints, we generate the carbon footprint for the petroleum products sales sector globally.

TABLE 17: CATEGORIZATION OF THE CARBON FOOTPRINT OF THE PETROLEUM PRODUCTS SALES SECTOR

SECTOR	STAGES IN LIFE-CYCLE CRUDE OIL EMISSIONS MODEL	SCOPE FOR REFINING SECTOR
UPSTREAM	Exploration	Cat 1 & 3
	Drilling & Development	Cat 1 & 3
	Production & Extraction	Cat 1 & 3
	Surface Processing	Cat 1 & 3
	Maintenance	Cat 1 & 3
	Waste disposal	Cat 5
	Transport from Oil Fields to Refinery	Cat 1 & 3
	Offsite Emissions	Cat 1 & 3
MIDSTREAM	Refinery Emissions	Cat 1 & 3
DOWNSTREAM	Transporting from Refinery to Retail Market	Scope 1 & 2
	Combustion of Sold Products	Cat 11

Notes:

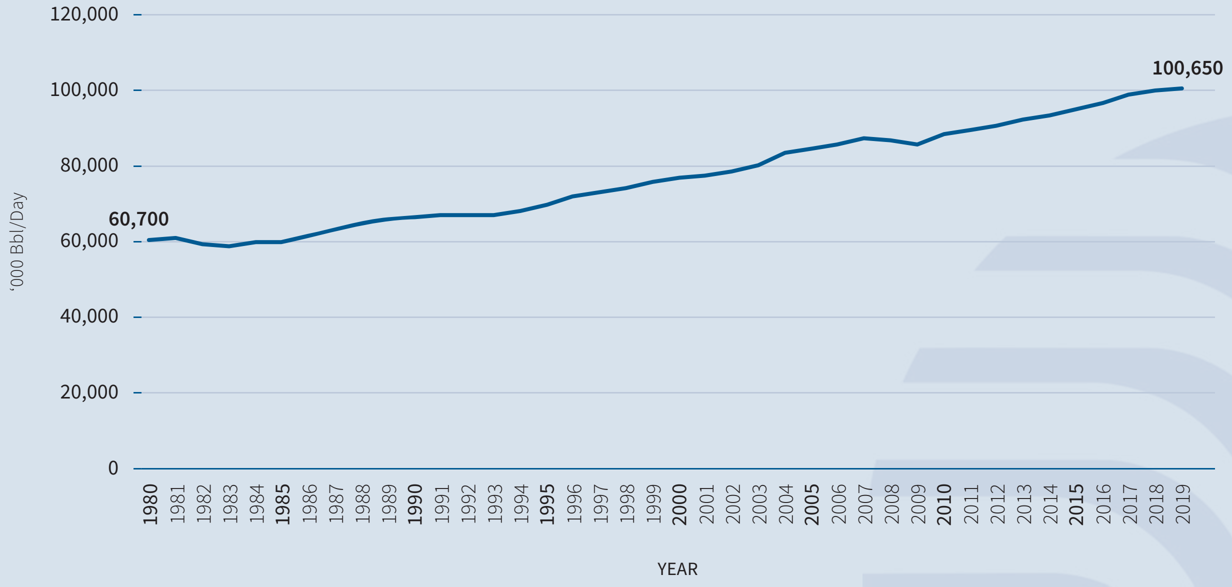
🟩 Scope 3 emissions from upstream
🟦 Scope 1 and 2 emissions
🟨 Scope 3 emissions from downstream

Cat 1	Purchased goods and services
Cat 3	Fuel and energy
Cat 5	Waste generated in operations
Cat 11	Use of sold products

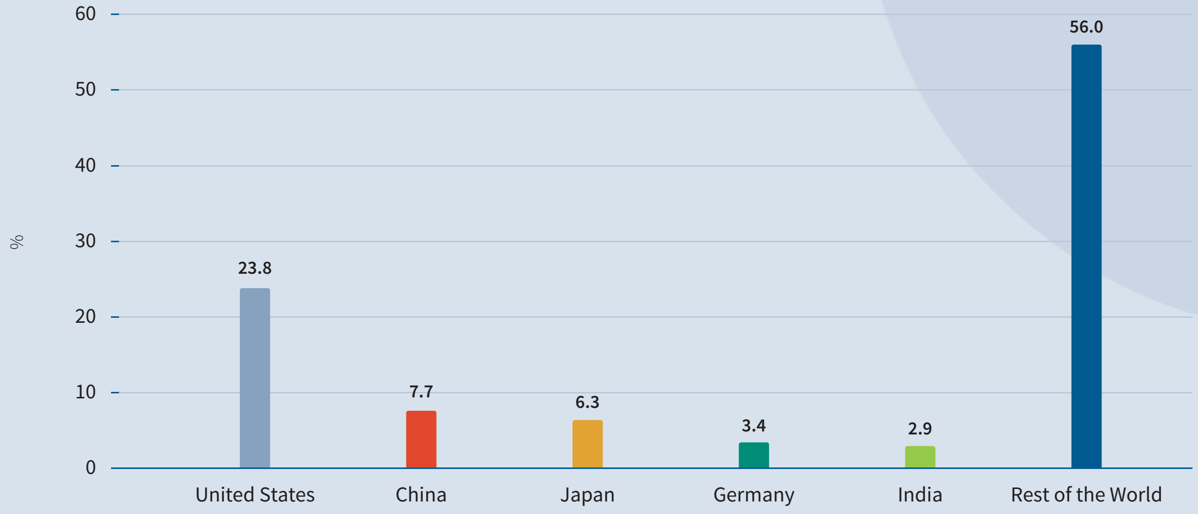
Source: *Prepared by the authors.*

FIGURE 15: PETROLEUM PRODUCTS CONSUMPTION DATA SUMMARY 1980–2019

GLOBAL CONSUMPTION OF PETROLEUM PRODUCTS



TOP 5 OIL CONSUMING COUNTRIES (AVERAGE FROM 1980–2019)



Source: *Global petroleum liquids consumption (U.S. Energy Information Administration 2021a).*

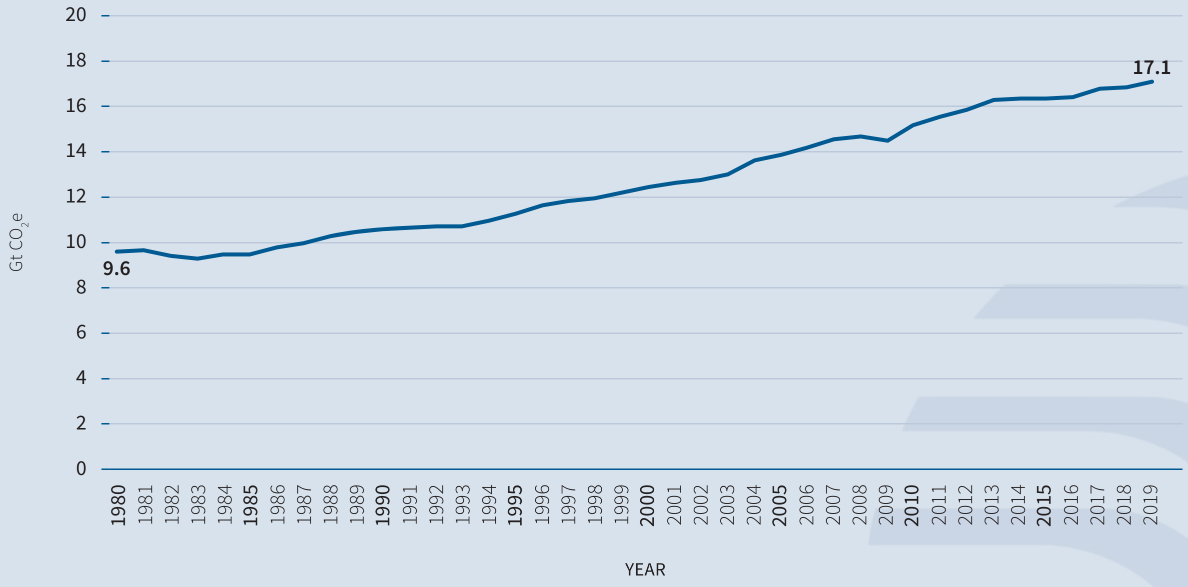
From 1980 to 2019, the global petroleum sales sector sold 1,128.06 billion barrels of petroleum products, leading to emissions of 508.43 Gt CO_2e, according to our model. On average, the sector sold 28.20 billion barrels of petroleum products per year; to produce, process, refine, transport, and combust these products, the whole oil value chain released a yearly average of 12.71 Gt CO_2e, according to our model. The annual carbon footprint of the global sector nearly doubled from 1980 to 2019, which reflects the increasing trend of consumption of petroleum products over the period of study.

4.1.3. Supermajors

4.1.3.1. BP

BP is a British oil company involved in every stage of the oil value chain. We gather its volume of sales of petroleum products from 2008 to 2019 from the Bloomberg Terminal (Bloomberg LP 2021a). To address data availability constraints, based on the high correlation coefficient between BP's oil production and petroleum sales between 2008 and 2018 (74.99%), we apply the percentage of change in BP's oil production[28] to estimate the company's petroleum products sales from 1980 to 2007 (Climate Accountability Institute, 2020). We break down BP's sales volume from 2004 to 2019 by country based on the revenue-based geographic distribution of BP's revenue (Bloomberg LP 2021b). To address the lack of data for 1980–2004, we apply the geographic distribution of BP's revenue by country in 2004 to previous years and apply the geographic distribution in 2018 to 2019 (see Figure 17).

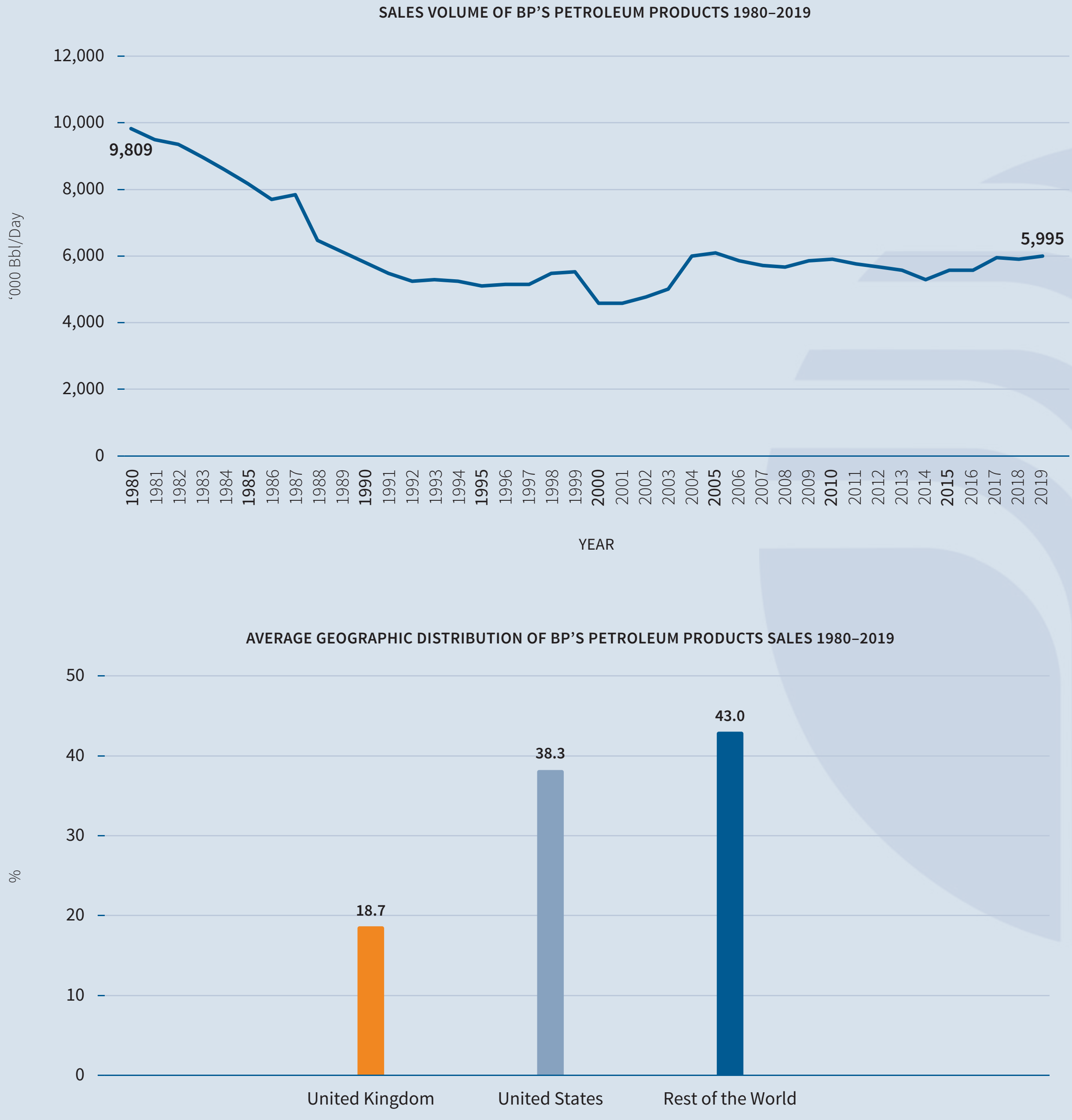
FIGURE 16: ANNUAL CARBON FOOTPRINT OF THE GLOBAL PETROLEUM PRODUCTS SALES SECTOR 1980–2019



FOOTNOTES

[28] Oil production data of supermajors used throughout this section is sourced from Climate Accountability Institute's Carbon Majors 2018 Data Set released in December 2020. The data from the Climate Accountability Institute accounts for the M&A effect of the oil companies, adding time-series data of acquired companies to mergers.

FIGURE 17: SUMMARY OF BP'S PETROLEUM PRODUCTS SALES DATA 1980–2019



BP's sales volume of petroleum products gradually decreases from 9.8 million barrels per day in 1980 to 6.0 million barrels per day in 2019. BP's sales have been mainly concentrated in the United Kingdom and the United States, and the sales in these two countries on average have accounted for 56.99% of BP's petroleum products sales.

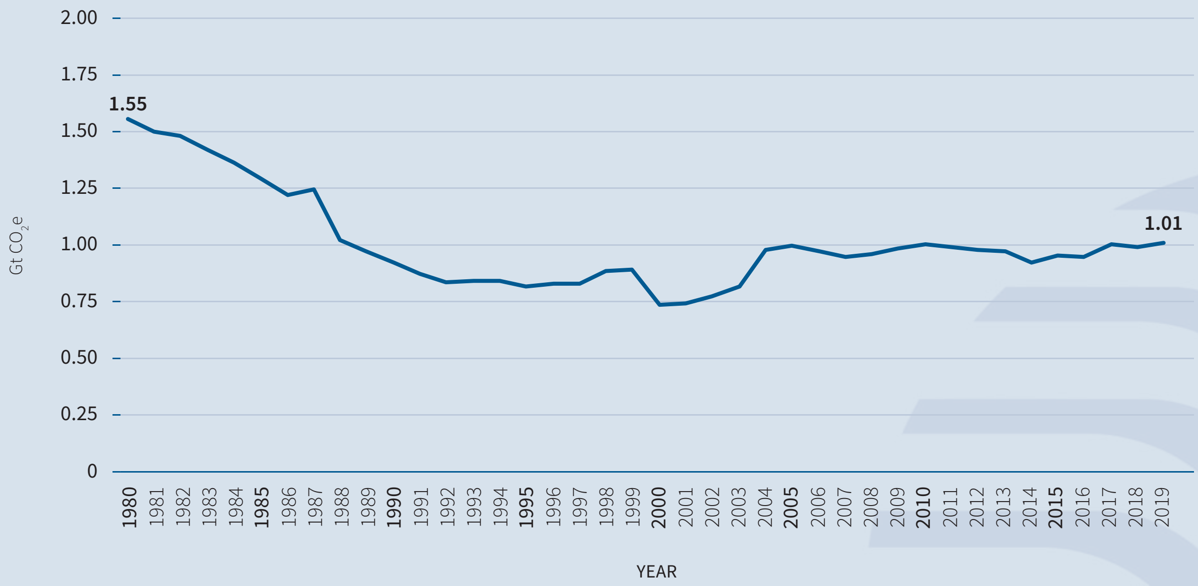
We then apply the corresponding country-specific life-cycle GHG emission factors by year and destination country to the data on BP's petroleum products sales to estimate the carbon footprint of BP's petroleum products sales segment over time.

From 1980 to 2019, BP's petroleum products sales segment is estimated to account for 40.39 Gt CO_2e released from the 90.41 billion barrels of petroleum products sold during the 40-year period. The average annual carbon footprint of BP's petroleum products sales segment accounted for 8.44% of the global sector during 1980–2019. Due to the decrease in sales volume, the annual carbon footprint of BP's petroleum products sales segment decreased from 1.55 Gt CO_2e in 1980 to 1.01 Gt CO_2e in 2019 (see Figure 18).

4.1.3.2. Chevron

Chevron is an American oil company. We gather its sales volume of petroleum products and volume-based geographic breakdown for 2005–2019 from its supplementary annual reports (Chevron 2011; Chevron 2016; Chevron 2020). Even though the correlation coefficient between Chevron's production and sales of petroleum products was only 9.01% between 2008 and 2018,[29] in order to address data availability constraints, we apply the percentage of change in Chevron's production of petroleum products[30] to estimate the company's petroleum products sales from 1980 to 2005. We also apply the geographic distribution of Chevron's sales by country in 2005 to previous years (see Figure 19). Chevron's sales volume of petroleum products remained stable from 1980 to 2000 and then gradually decreased to 2.58 million barrels per day in 2019. Chevron's sales of petroleum products are concentrated in the United States, which accounted for 40.8% of its petroleum products sales on average.

FIGURE 18: ANNUAL CARBON FOOTPRINT OF BP'S PETROLEUM PRODUCTS SALES SEGMENT 1980–2019

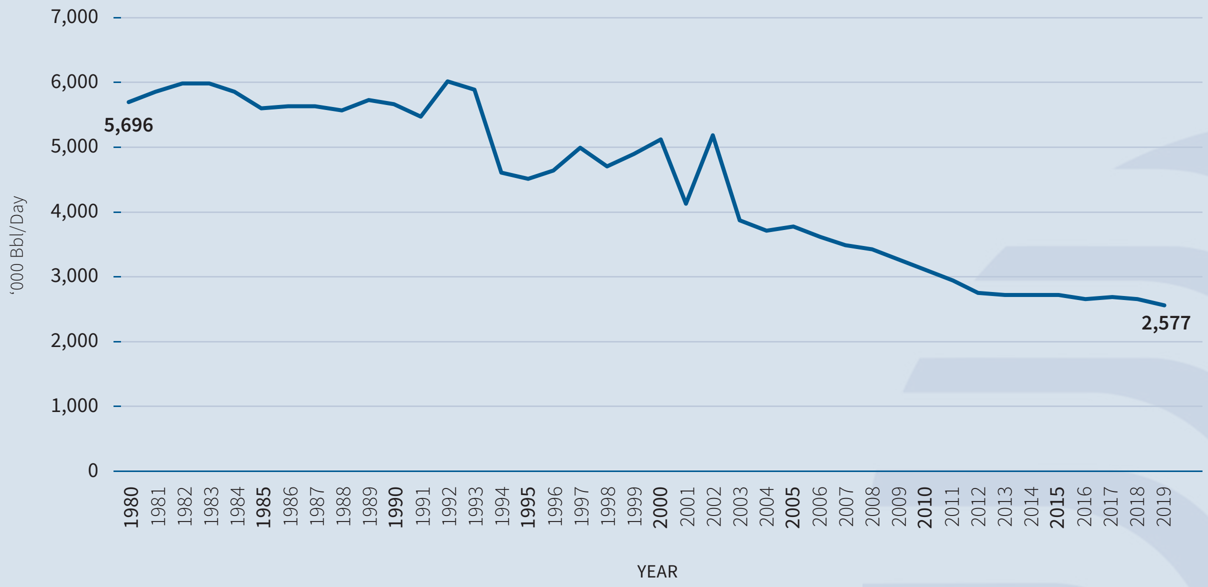


FOOTNOTES

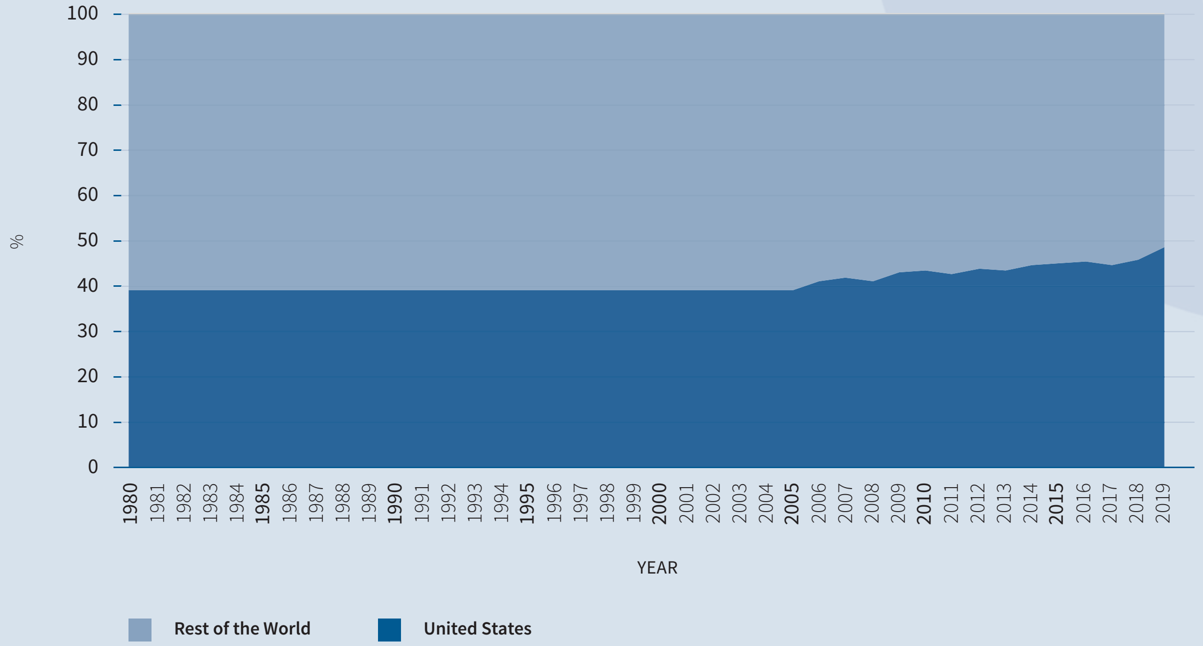
[29] Chevron's poor correlation between petroleum products production and sales may be due to its poor inventory turnover ratio. Its average quarterly inventory turnover from 2008 to 2021 was 17.52, which was ranked No. 7 in Oil & Gas Integrated Operations Industry and No. 30 in Energy Sector. (CSIMarket 2021)

[30] Since the correlation between Chevron's oil production data and its petroleum products sales from 2008 to 2018 is -21.36%, we apply the change rate of its petroleum products production data from Refinery Report in Oil & Gas Journal (2019) to simulate its petroleum products sales instead.

FIGURE 19: SUMMARY OF CHEVRON'S PETROLEUM PRODUCTS SALES DATA 1980–2019



VOLUME OF CHEVRON'S PETROLEUM PRODUCTS 1980–2019



GEOGRAPHIC DISTRIBUTION OF CHEVRON'S PETROLEUM PRODUCTS SALES (AVERAGE FROM 1980–2019)

We then apply the corresponding U.S. and weighted-average worldwide life-cycle GHG emission factors by year to the data on Chevron's petroleum products sales to estimate the carbon footprint of Chevron's petroleum products sales segment over time.

From 1980 to 2019, Chevron's petroleum products sales segment is estimated to account for 28.66 Gt CO_2e released from the 64.31 billion barrels of petroleum products sold. The average annual carbon footprint of Chevron's petroleum products sales segment accounted for 7.48% of the global sector during 1980–2019. The annual carbon footprint of Chevron's petroleum products sales segment followed a trend similar to its sales volume of petroleum products, which decreased from 903.02 Mt CO_2e in 1980 to 440.84 Mt CO_2e in 2019 (see Figure 20).

4.1.3.3. Eni

Eni is an Italian oil company. We gather its sales volume of petroleum products and volume-based geographic breakdown for 2007–2019 from its fact book (Eni 2012; Eni 2015; Eni 2018; Eni 2021). To address the lack of publicly available data, based on the relatively high correlation coefficient between Eni's oil production and petroleum sales between 2007 and 2018 (51.67%), we apply the percentage of change in Eni's oil production to estimate its petroleum products sales from 1980 to 2006. We also apply the geographic breakdown in 2007 to previous years (see Figure 21).

FIGURE 20: ANNUAL CARBON FOOTPRINT OF CHEVRON'S PETROLEUM PRODUCTS SALES SEGMENT 1980–2019

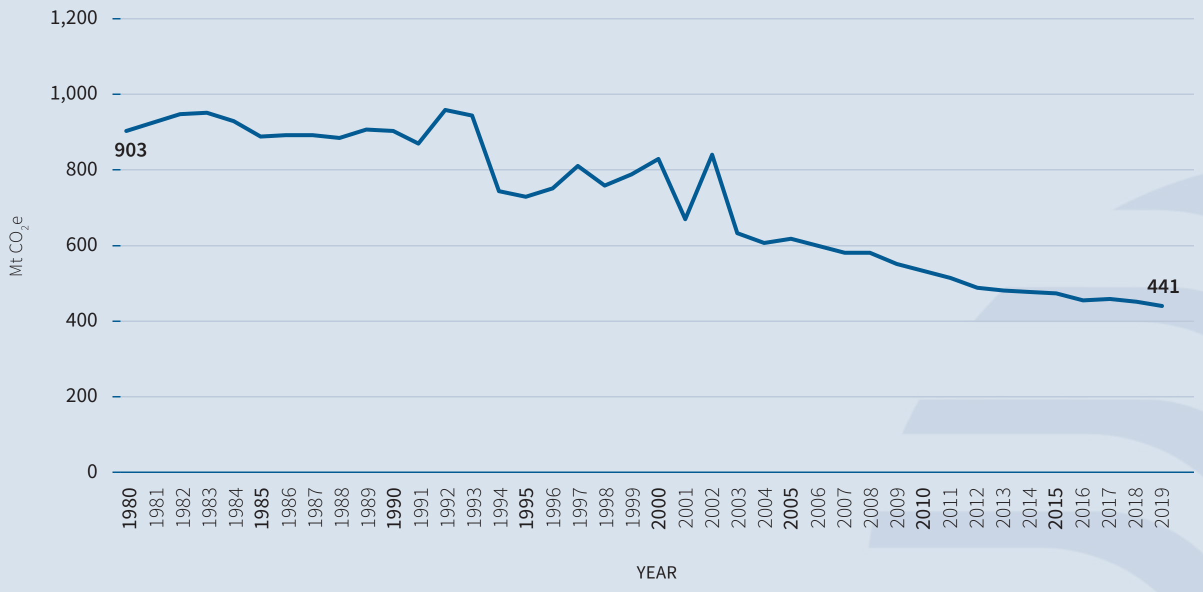
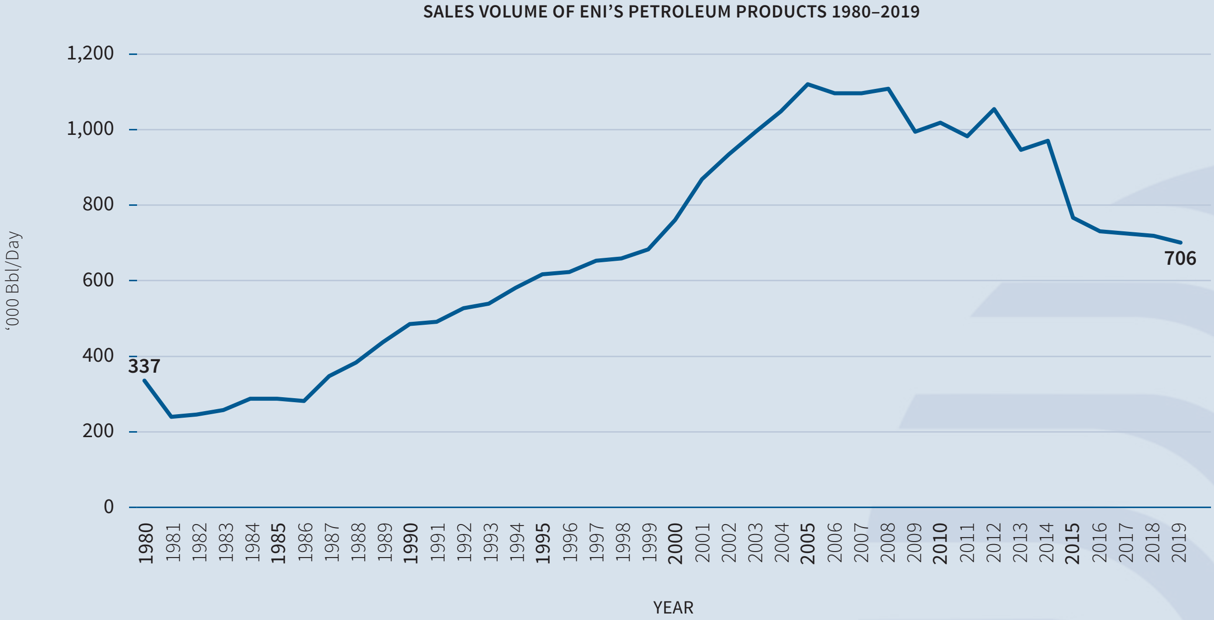
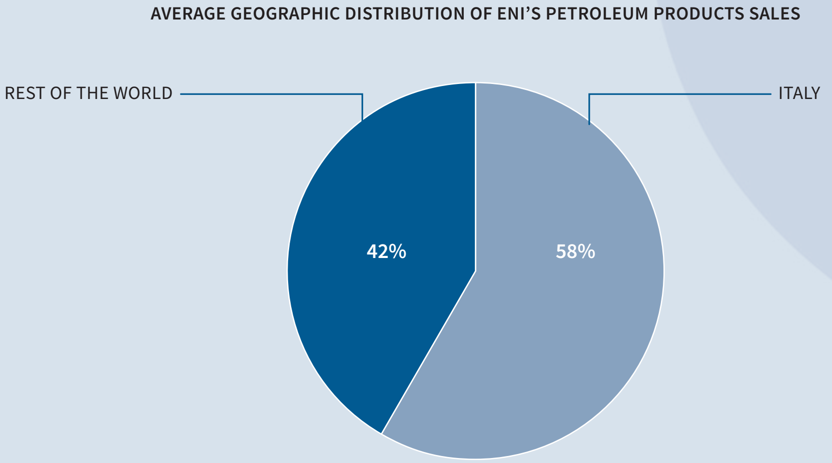


FIGURE 21: SUMMARY OF ENI'S PETROLEUM PRODUCTS SALES DATA 1980–2019





Source: *Eni Factbook (Eni 2012; Eni 2015; Eni 2018; Eni 2021).*

Eni's sales volume of petroleum products increased from 0.337 million to 1.125 million barrels per day from 1980 to 2005 and then dropped to 0.706 million barrels per day in 2019. Its sales of petroleum products have been concentrated in Europe, especially Italy, which accounted for 58.47% of its petroleum products sales on average.

We then apply the corresponding country-specific life-cycle GHG emission factors by year and region to the data on Eni's petroleum products sales to estimate the carbon footprint of Eni's petroleum products sales segment over time.

From 1980 to 2019, Eni's petroleum products sales segment is estimated to account for 4.45 Gt CO_2e released from the 10.32 billion barrels of petroleum products sold. The average annual carbon footprint of Eni's petroleum products sales segment accounted for 0.85% of the global sector during 1980–2019. The annual carbon footprint of Eni's petroleum products sales segment increased from 52.48 Mt CO_2e in 1980 to 179.08 Mt CO_2e in 2005 and then gradually decreased to 114.82 Mt CO_2e in 2019, which aligns with the trend of petroleum products sales (see Figure 22).

4.1.3.4. ExxonMobil

ExxonMobil is an American oil company. We gather its sales volume of petroleum products for 2001–2019 from the ExxonMobil Financial & Operational Review (ExxonMobil 2005; ExxonMobil 2010; ExxonMobil 2014; ExxonMobil 2018; ExxonMobil 2021a). To address the lack of publicly available data, based on the relatively high correlation coefficient between ExxonMobil's oil production and petroleum sales between 2001 and 2018 (77.30%), we apply the percentage of change in ExxonMobil's oil production to estimate its petroleum products sales from 1980 to 2000. We obtained the revenue-based distribution of ExxonMobil's petroleum products sales by destination country for 2000–2019 from Bloomberg Terminal (Bloomberg LP 2021b). To address the lack of publicly available data for 1980–2000, we apply the geographic distribution of Exxon's revenues by country in 2000 to previous years (see Figure 23). ExxonMobil's sales volume of petroleum products increased from 5.93 million barrels per day in 1980 to 8.00 million barrels per day in 1988 and then gradually decreased to 5.45 million barrels per day in 2019. ExxonMobil's sales of petroleum products have been concentrated in the United States, Canada, the United Kingdom, and Japan (ExxonMobil 2021a). The sales in these four countries, on average, have accounted for 78% of its petroleum products sales.

FIGURE 22: CARBON FOOTPRINT OF ENI'S PETROLEUM PRODUCTS SALES SEGMENT 1980–2019

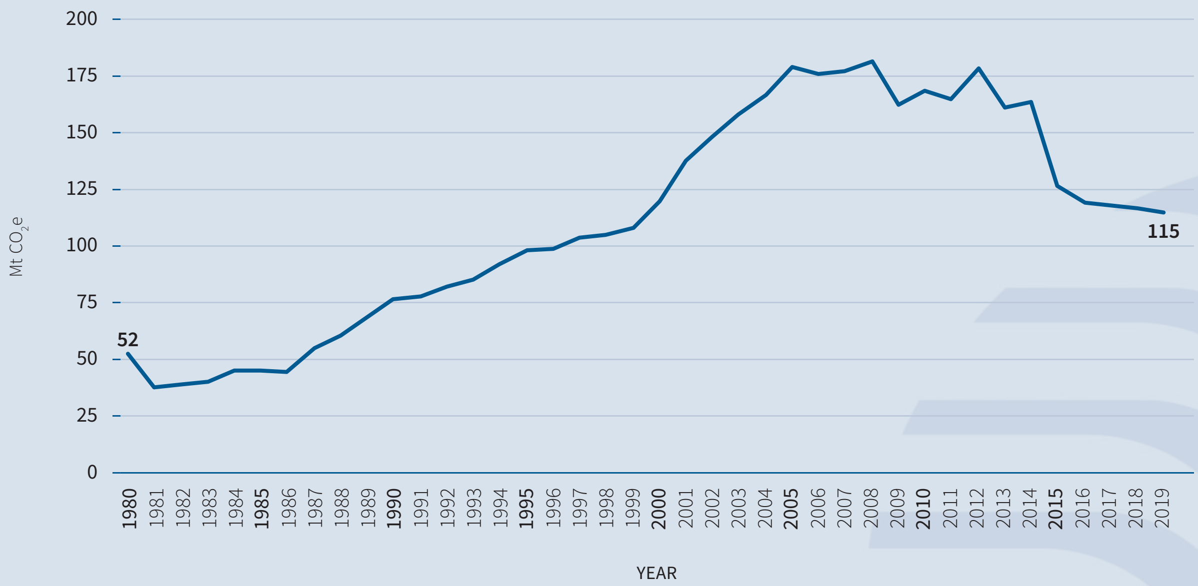
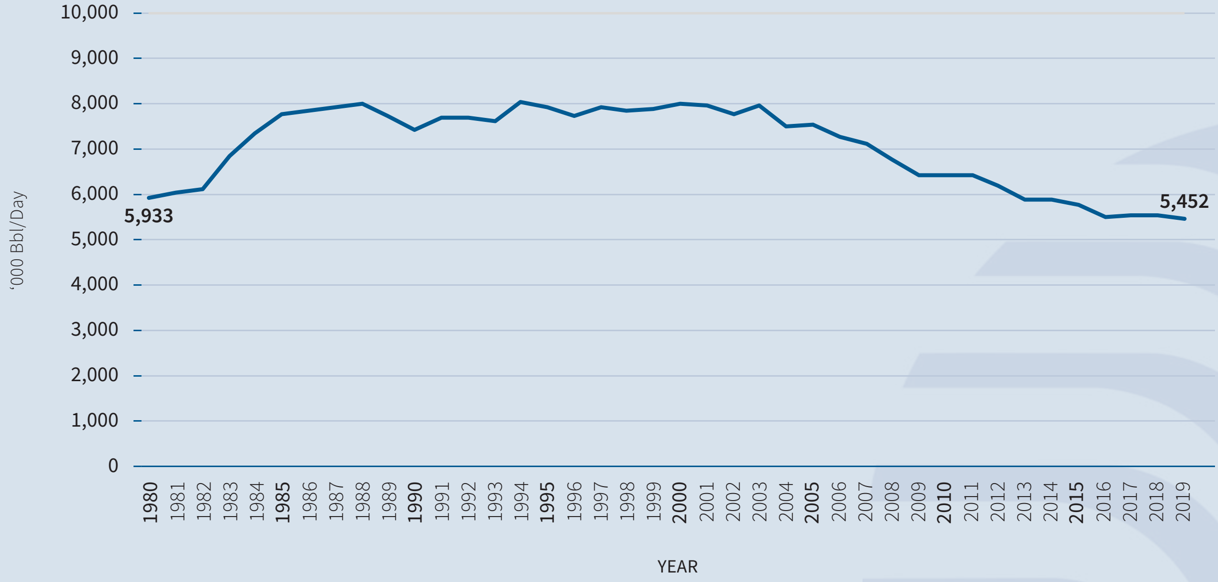
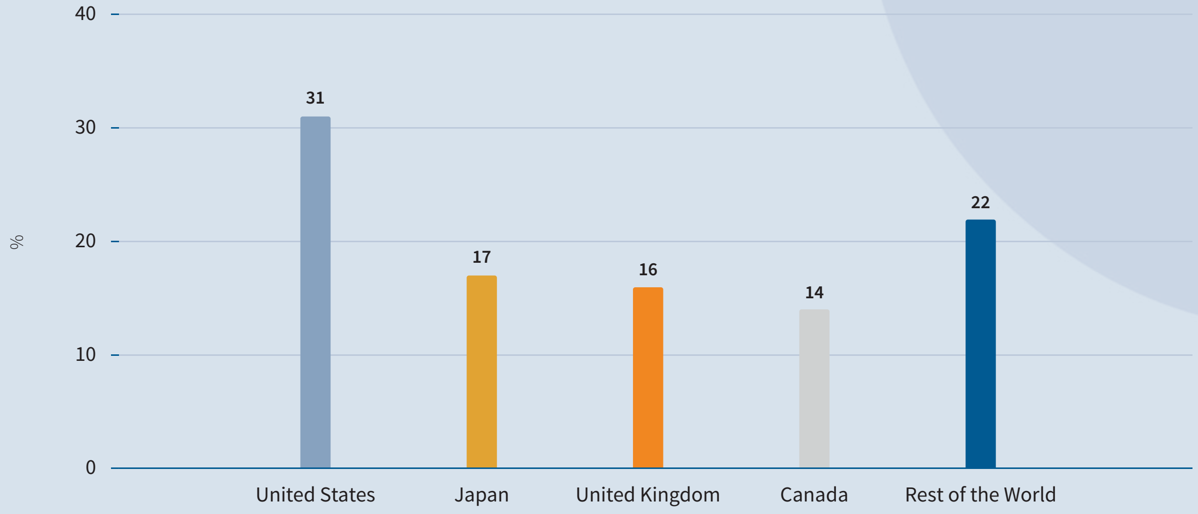


FIGURE 23: SUMMARY OF EXXONMOBIL’S PETROLEUM PRODUCTS SALES DATA 1980–2019

SALES VOLUME OF EXXONMOBIL’S PETROLEUM PRODUCTS 1980–2019



AVERAGE GEOGRAPHIC DISTRIBUTION OF EXXONMOBIL’S PETROLEUM PRODUCTS SALES



We then apply the corresponding country-specific life-cycle GHG emission factors by year and destination country to the data on ExxonMobil's petroleum products sales to estimate the carbon footprint of ExxonMobil's petroleum products sales segment over time.

From 1980 to 2019, ExxonMobil's petroleum products sales segment is estimated to account for 46.19 Gt CO_2e released from the 102.93 billion barrels of petroleum products sold. The annual average carbon footprint of ExxonMobil's petroleum products sales segment accounted for 9.52% of the global sector during 1980–2019. Due to the fluctuation of the sales volume, the annual carbon footprint of ExxonMobil's petroleum products sales segment increased from 0.94 Gt CO_2e in 1980 to 1.27 Gt CO_2e in 1988 and then gradually decreased to 0.93 Gt CO_2e in 2019 (see Figure 24).

4.1.3.5. Shell

Shell is a British–Dutch oil company. We gather its sales volume of petroleum products and volume-based geographic breakdown from 2007 to 2019 from its investors' handbook (Shell 2012; Shell 2015; Shell 2020). To address data availability constraints, based on a relatively high correlation coefficient between Shell's oil production and petroleum products sales between 2007 and 2018 (56.93%), we apply the percentage of change in Shell's oil production to estimate Shell petroleum products sales from 1980 to 2006. To address the lack of data for 1980–2006, we apply the geographic distribution of Shell's revenues by country in 2007 to previous years (see Figure 25). Shell's sales volume of petroleum products increased from 4.7 million barrels per day in 1980 to 8.76 million barrels per day in 2000 and then dropped to 6.56 million barrels per day in 2019. Shell's sales of petroleum products have been concentrated in Europe, the Americas, and Asia–Pacific; the sales in these three regions respectively account for 37.1%, 34.8%, and 20.9% of Shell's sales of petroleum products on average (Shell 2020).

FIGURE 24: ANNUAL CARBON FOOTPRINT OF EXXONMOBIL'S PETROLEUM PRODUCTS SALES SEGMENT 1980–2019

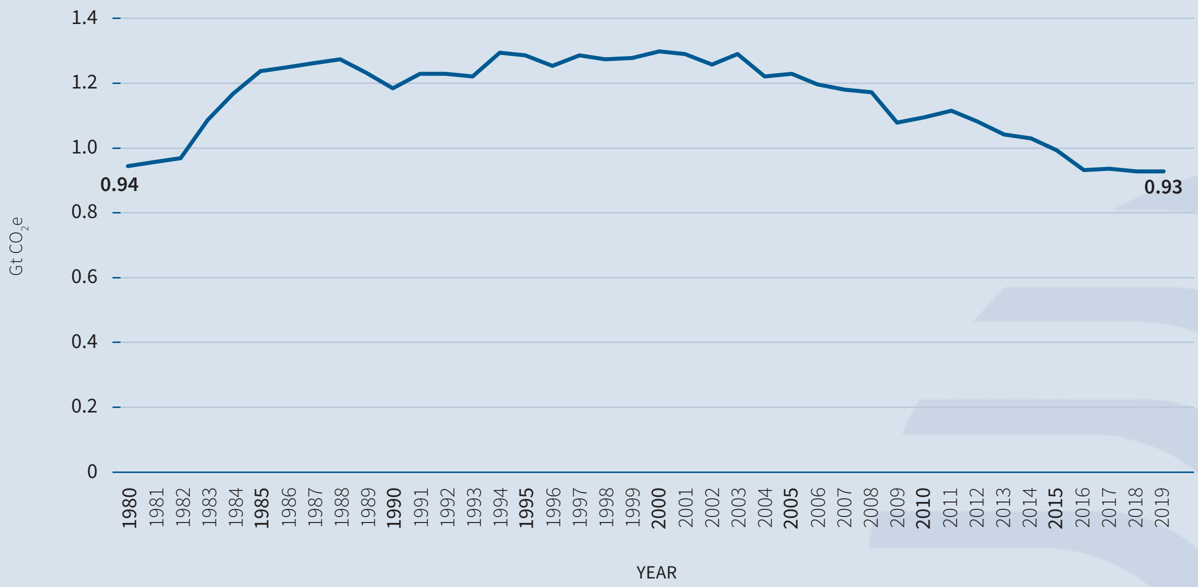
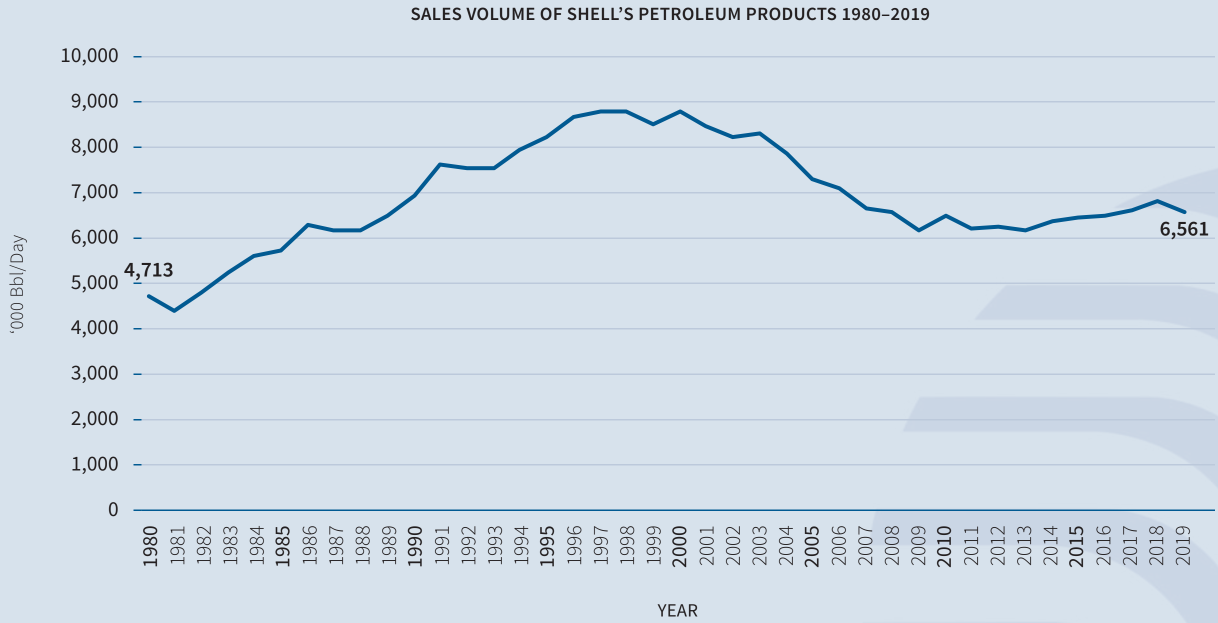
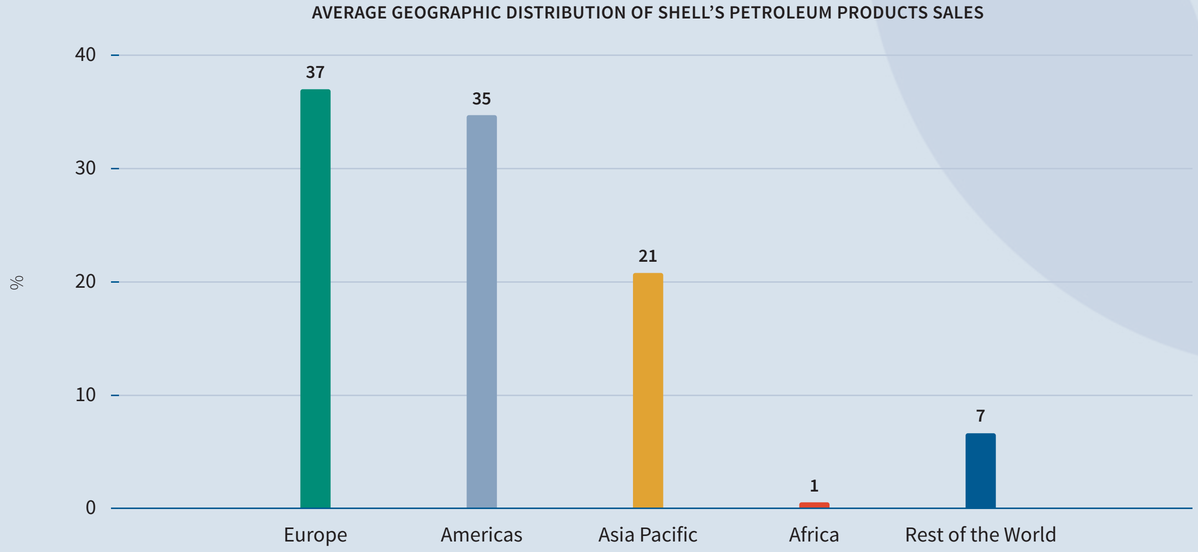


FIGURE 25: SUMMARY OF SHELL'S PETROLEUM PRODUCTS SALES DATA 1980–2019





We then apply the corresponding country-specific life-cycle GHG emission factors by year and destination country to the data on Shell's petroleum products sales to estimate the carbon footprint of Shell's petroleum products sales segment over time.

From 1980 to 2019, Shell's petroleum products sales segment is estimated to account for 44.44 Gt CO_2e released from the 100.58 billion barrels of petroleum products sold. The annual average carbon footprint of Shell's petroleum products sales segment accounted for 8.98% of the global sector during 1980–2019. Due to the fluctuation of the sales volume, the annual carbon footprint of Shell's petroleum products sales segment increased from 736.57 Mt CO_2e in 1980 to 1,395.41 Mt CO_2e in 1998 and then decreased to 1,099.30 Mt CO_2e in 2019 (see Figure 26).

4.1.3.6. TotalEnergies

TotalEnergies is a French oil company. We gather its sales volume of petroleum products and volume-based geographic breakdown from 2000–2019 from its factbook (TotalEnergies 2007; TotalEnergies 2010; TotalEnergies 2015; TotalEnergies 2020b). To address the lack of publicly available data, based on the relatively high correlation coefficient between TotalEnergies' oil production and petroleum sales between 2000 and 2018 (76.72%), we apply the percentage of change in TotalEnergies' oil production to estimate its petroleum products sales from 1980 to 1999. We also apply the geographic breakdown in 2000 to previous years (see Figure 27). TotalEnergies' sales volume of petroleum products increased sharply from 1.075 million to 3.277 million barrels per day from 1981 to 1995 and then gradually dropped to 1.845 million barrels per day in 2019. TotalEnergies' sales of petroleum products have been concentrated in Europe, which accounts for 71% of its petroleum products sales.

FIGURE 26: CARBON FOOTPRINT OF SHELL'S PETROLEUM PRODUCTS SALES SEGMENT 1980–2019

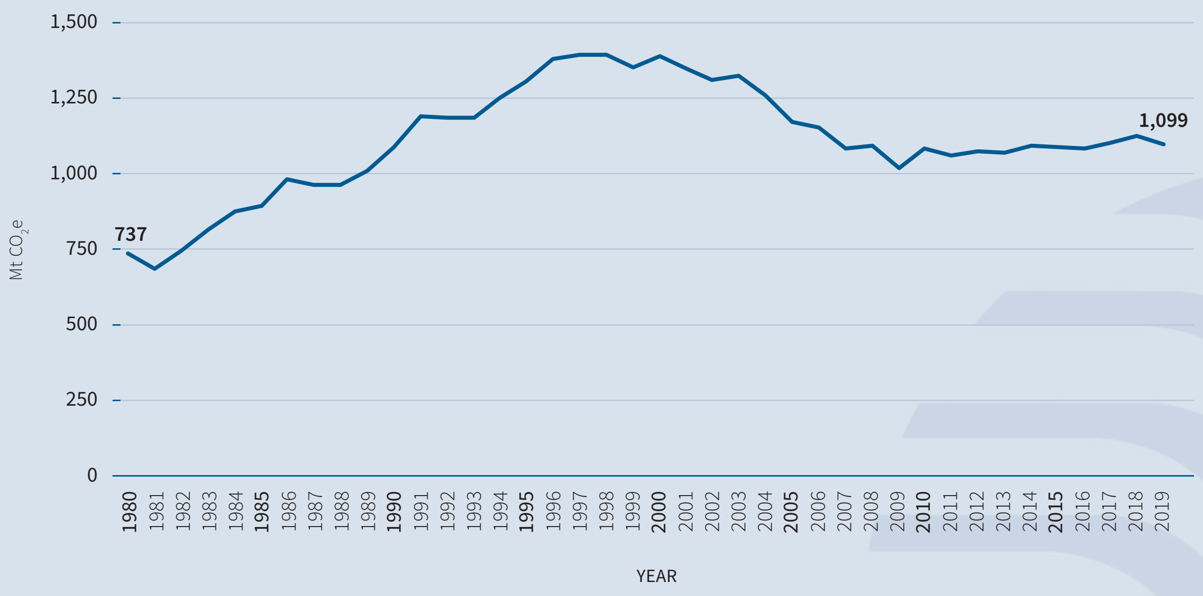
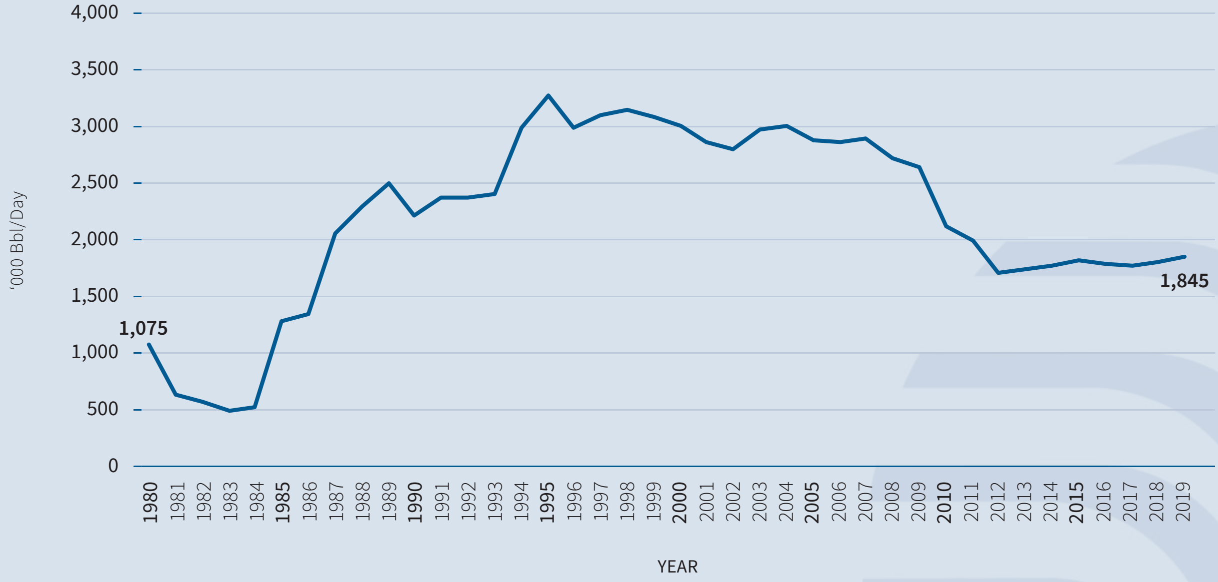
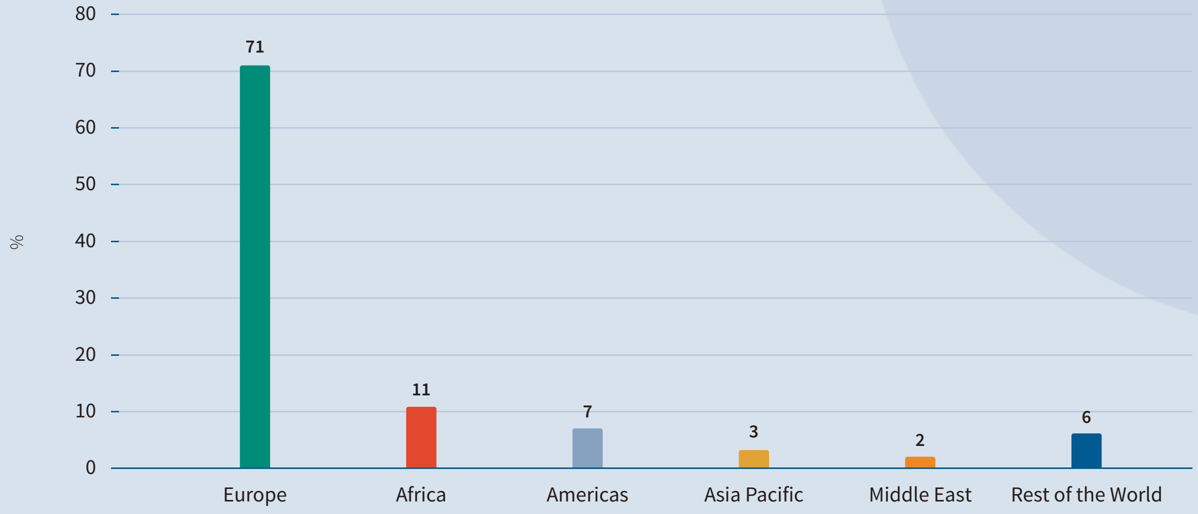


FIGURE 27: SUMMARY OF TOTALENERGIES' PETROLEUM PRODUCTS SALES DATA 1980–2019


SALES VOLUME OF TOTALENERGIES' PETROLEUM PRODUCTS 1980–2019

AVERAGE GEOGRAPHIC DISTRIBUTION OF TOTALENERGIES' PETROLEUM PRODUCTS SALES



Source: *TotalEnergies Factbook (TotalEnergies 2007; TotalEnergies 2010; TotalEnergies 2015; TotalEnergies 2020b).*

We then apply the corresponding country-specific life-cycle GHG emission factors by year and region to the data on TotalEnergies' petroleum products sales to estimate the carbon footprint of TotalEnergies' petroleum products sales segment over time.

From 1980 to 2019, TotalEnergies' petroleum products sales segment is estimated to account for 13.98 Gt CO_2e released from the 32.04 billion barrels of petroleum products sold. The annual average carbon footprint of TotalEnergies' petroleum products sales segment accounted for 2.78% of the global sector during 1980–2019. The annual carbon footprint of TotalEnergies' petroleum products sales segment sharply increased from 167 Mt CO_2e in 1980 to 515 Mt CO_2e in 1995 and then gradually decreased to 302 Mt CO_2e in 2019, which aligns with the trend of petroleum products sales (see Figure 28).

4.1.3.7. Summary

From 1980 to 2019, the petroleum products sales segment of the supermajors is estimated to account for 178.11 Gt CO_2e released from the 400.59 billion barrels of petroleum products sold, which accounts for 35.03% of the carbon footprint of the global petroleum products sales sector during 1980–2019.

FIGURE 28: ANNUAL CARBON FOOTPRINT OF TOTALENERGIES' PETROLEUM PRODUCTS SALES SEGMENT 1980–2019

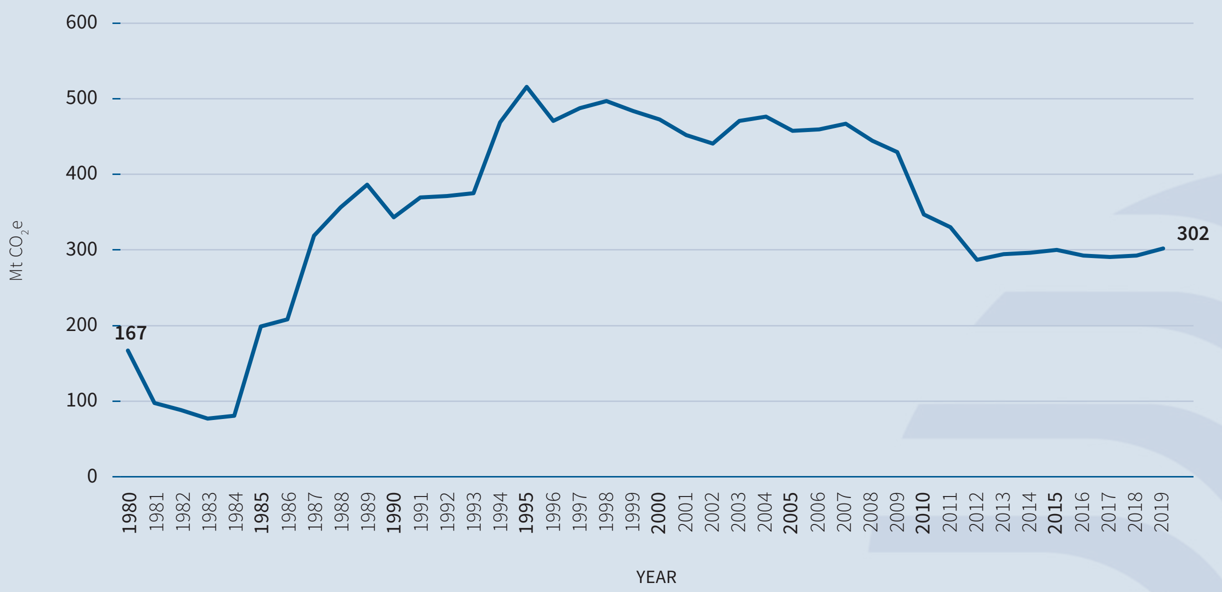


FIGURE 29: ANNUAL CARBON FOOTPRINT OF THE PETROLEUM SALES SECTOR OF THE SUPERMAJORS

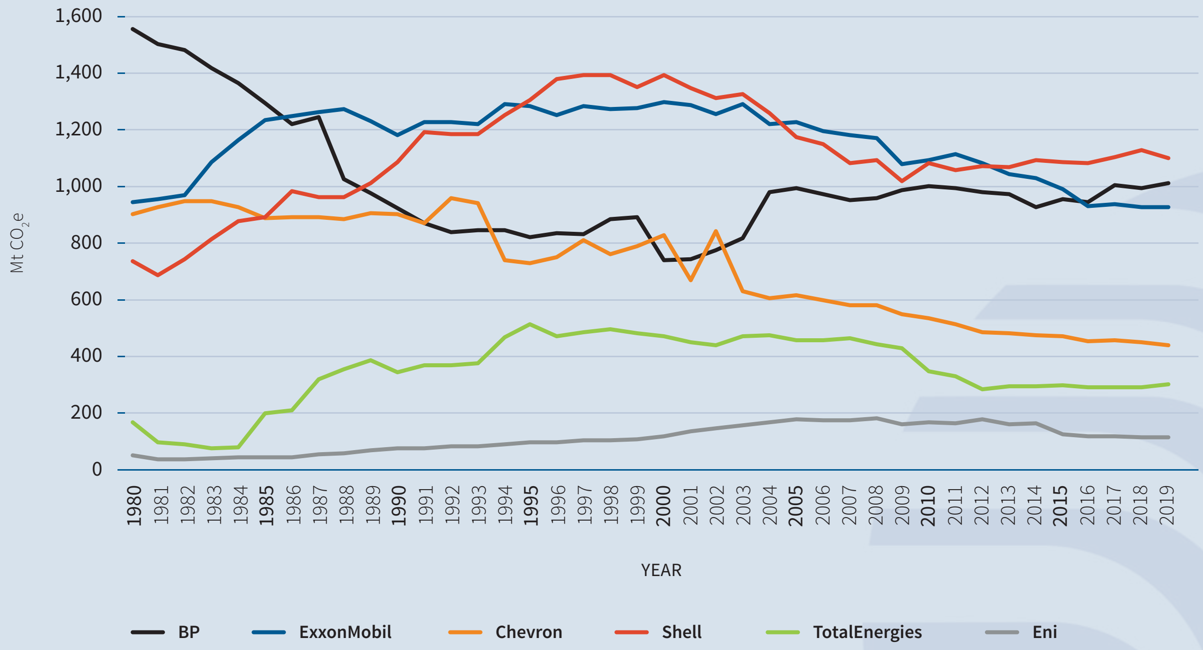
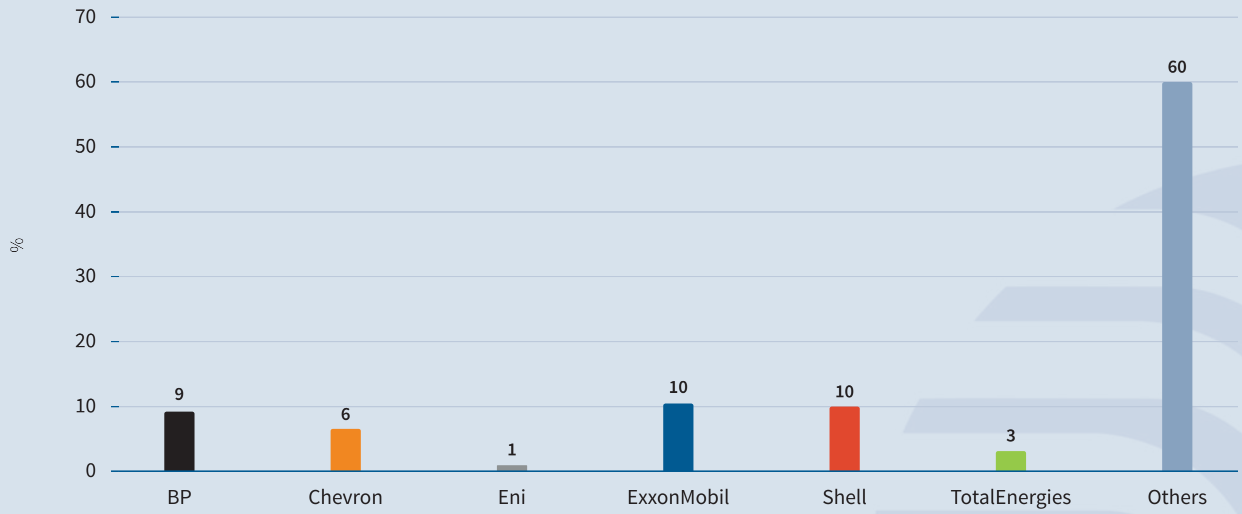


FIGURE 30: CUMULATIVE CARBON FOOTPRINTS OF THE SUPERMAJORS' PETROLEUM SALES SEGMENTS 1980–2019



4.2. CARBON FOOTPRINT OF THE REFINING SECTOR

4.2.1. Boundaries

According to IPIECA's definitions, the carbon footprint of the refining sector does not only include scopes 1 and 2 emissions from refining operations, but also scope 3 emissions, which include process emissions from producing the crude oil used in refineries, the emissions from transporting and distributing refined products to the petroleum products sales sector, and the emissions from the use of petroleum products (IPIECA 2011). See Table 18 to visualize how the stages of the value chain covered by this study to assess the refinery sector's carbon footprint match with the scopes and scope 3 categories defined by IPIECA.

4.2.2. Global Refining Sector

To quantify the carbon footprint of the global refining sector, we collect data on the global refinery output from 1980 to 2019 from BP's statistical review (2020d). The global sector refined 984.45 billion barrels of crude oil during the period, and Asia–Pacific and the Middle East were the largest producers of refined products (see Figure 31).

TABLE 18: CATEGORIZATION OF THE CARBON FOOTPRINT OF THE REFINING SECTOR (IPIECA 2011)

SECTOR	STAGES IN LIFE-CYCLE CRUDE OIL EMISSIONS MODEL	SCOPE FOR REFINING SECTOR
UPSTREAM	Exploration	Cat 1 & 3
	Drilling & Development	Cat 1 & 3
	Production & Extraction	Cat 1 & 3
	Surface Processing	Cat 1 & 3
	Maintenance	Cat 1 & 3
	Waste disposal	Cat 5
	Transport from Oil Fields to Refinery	Cat 1 & 3
	Offsite Emissions	Cat 1 & 3
MIDSTREAM	Refinery Emissions	Scope 1 & 2
DOWNSTREAM	Transporting from Refinery to Retail Market	Cat 9
	Combustion of Sold Products	Cat 11

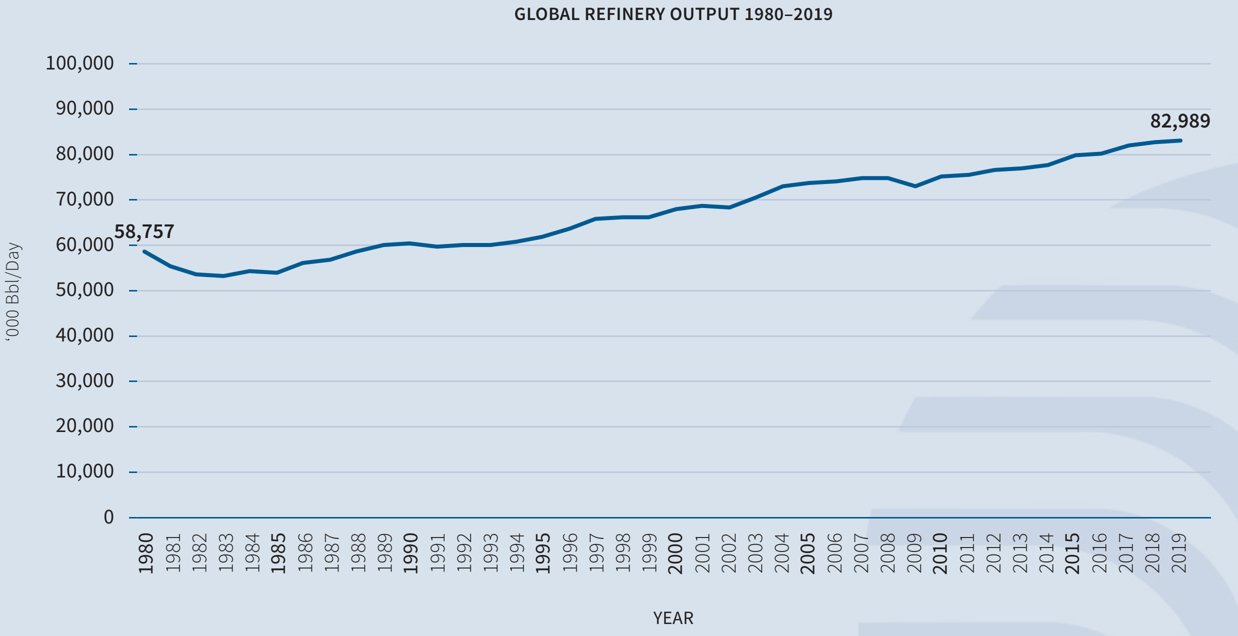
Notes:

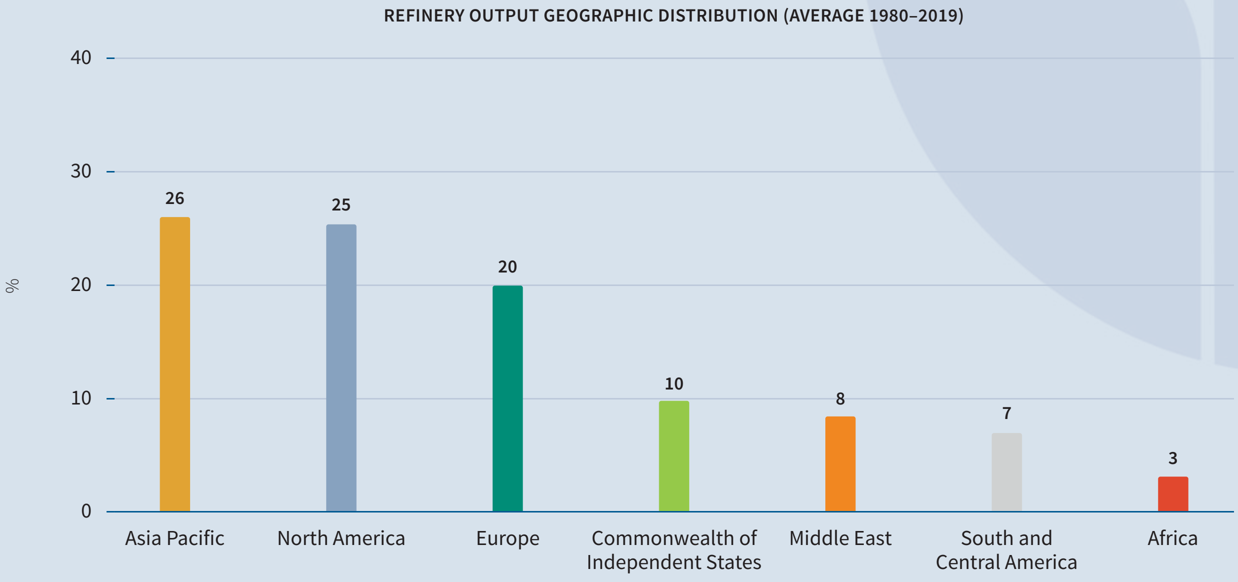
🟩 Scope 3 emissions from upstream
🟦 Scope 1 and 2 emissions
🟨 Scope 3 emissions from downstream

Cat 1	Purchased goods and services
Cat 3	Fuel and energy
Cat 5	Waste generated in operations
Cat 9	Downstream transportation and distribution
Cat 11	Use of sold products

Source: *Prepared by the authors.*

FIGURE 31: SUMMARY OF GLOBAL REFINERY OUTPUT DATA





We multiply the 83 countries' refinery output by the corresponding country-specific life-cycle emission factors resulting from our model to estimate the carbon footprint of the refinery sector by country. For countries not included in our model, we apply the global average emission factors while acknowledging that this results in a simplification. Consolidating the carbon footprints of all countries, we estimate the carbon footprint for the global refining sector. From 1980 to 2019, the global sector refined 984.45 billion barrels of crude oil, leading to emissions of 442.84 Gt CO_2e. The annual carbon footprint of the global refining sector increased steadily over time by 51.08% from 1980 to 2019, reflecting the increasing trend of oil extraction over the period of study.

4.2.3. Supermajors

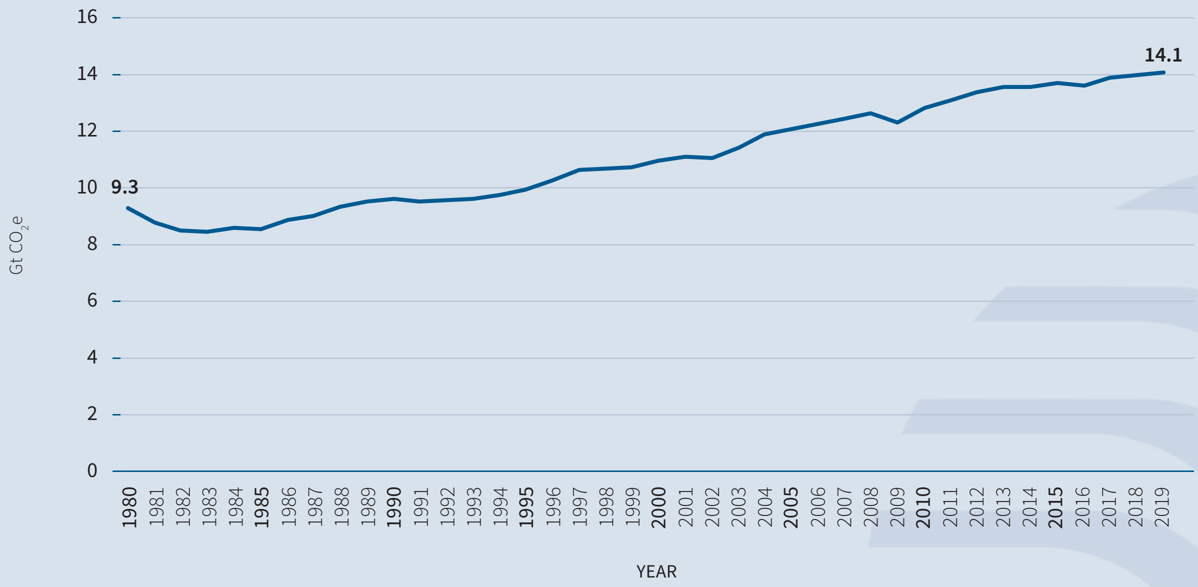
To analyze the carbon footprints of the six supermajors in the refining sector, we first gather their refining capacity, which refers to their maximum refinery output. We sourced the data from 1992 to 2014 from the Refinery Report in the Oil & Gas Journal (2019). To address the lack of publicly available data, we apply the ratio of each company's three-year average refining capacity to the global refining capacity to estimate the company's refining capacity from 1980 to 1991; the three years being the three years following the year for which we are calculating the data. We gather the companies' refining capacity in 2020 from McKinsey Refinery Capacity Database and apply interpolation to estimate the refining capacity from 2015 to 2019 (Fitzgibbon 2020).

$$\frac{\textit{Yr } n{+}3 \textit{ Global Refining Capacity}}{\textit{Yr } n{+}3 \textit{ Company A Refining Capacity}} = \frac{\textit{Average of Yr } n{,}n{+}1 \,\&\, n{+}2 \textit{ Global Refining Capacity}}{\textit{Average of Company A}\text{^'}\textit{s Yr } n{,}n{+}1 \,\&\, n{+}2 \textit{ Refining Capacity}}$$

Considering the effect of mergers and acquisitions on the refining capacity, we add the historical refining capacity of the acquired companies to the parent companies to better reflect the historical responsibility of the companies in CO_2 emissions. The refining capacity of Mobil Oil Corp. is added to ExxonMobil's; Texaco Inc.'s to Chevron's; Amoco Oil Co.'s to BP's; and Petrofina's to TotalEnergies'. To address the lack of continuous time-series refinery data for Elf Aquitaine, ARCO, Gulf Oil, Tenneco, Unocal in Refinery Report in the Oil & Gas Journal, we did not add Elf Aquitaine's data to TotalEnergies', ARCO's data to BP's, or data from Gulf Oil, Tenneco, and Unocal to Chevron's.

$$\textit{Refinery output} = \textit{Refining capacity} \times \textit{Capacity utilization}$$

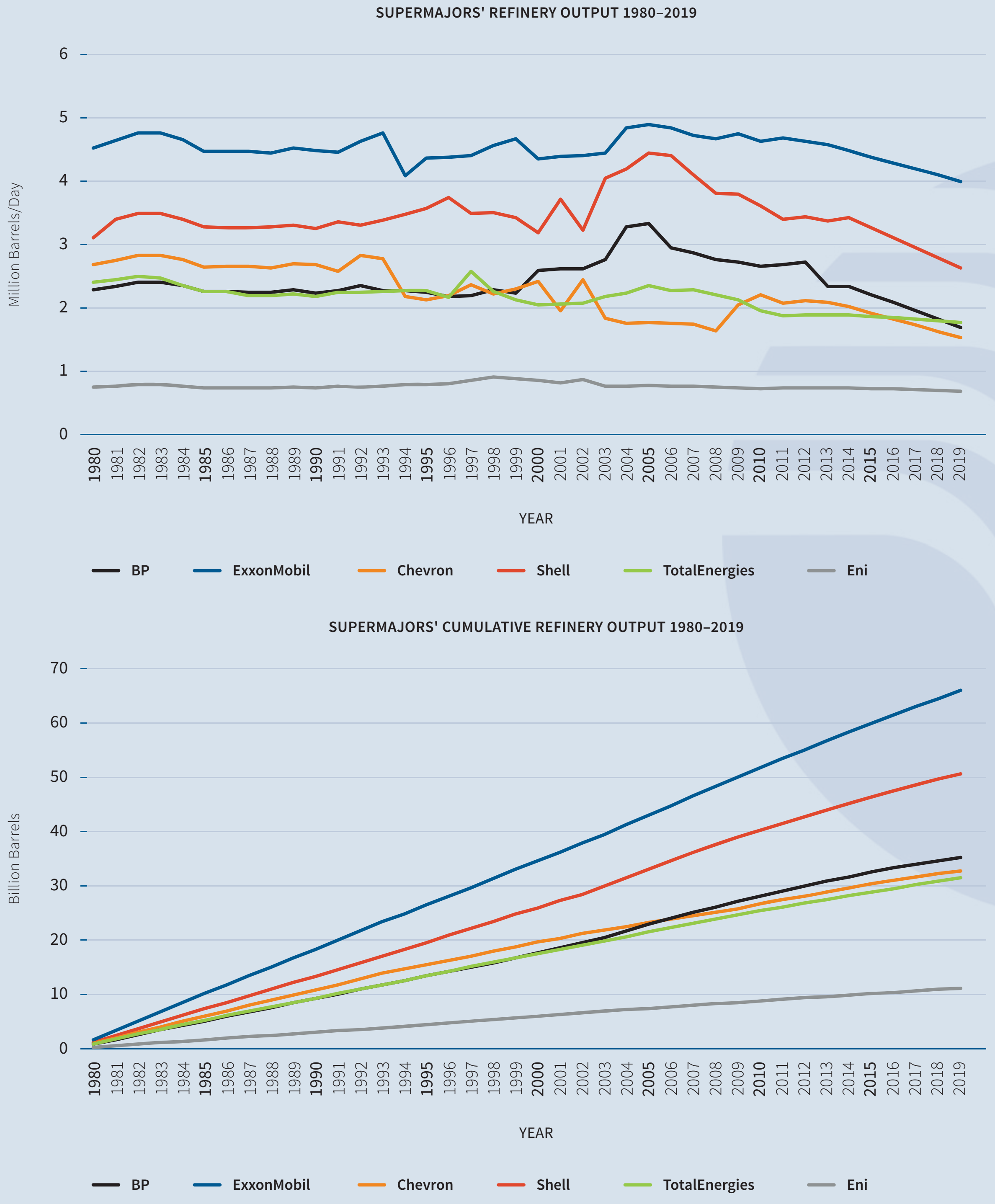
FIGURE 32: ANNUAL CARBON FOOTPRINT OF THE GLOBAL REFINING SECTOR 1980–2019



Second, we apply the global capacity utilization from BP statistics (BP 2020c) to the companies' refining capacity to estimate their refinery output. Global capacity utilization increased from 74% in 1980 to 82% in 2019, and the average global capacity utilization was 81% throughout the period (BP 2020c).

From 1980 to 2019, the total refinery output of the supermajors is 227.52 billion barrels, which accounts for 23.11% of the global refinery output during the period. Among the supermajors, ExxonMobil refined the biggest volume of crude oil (66.04 billion barrels), while Eni refined the smallest (11.18 billion barrels).

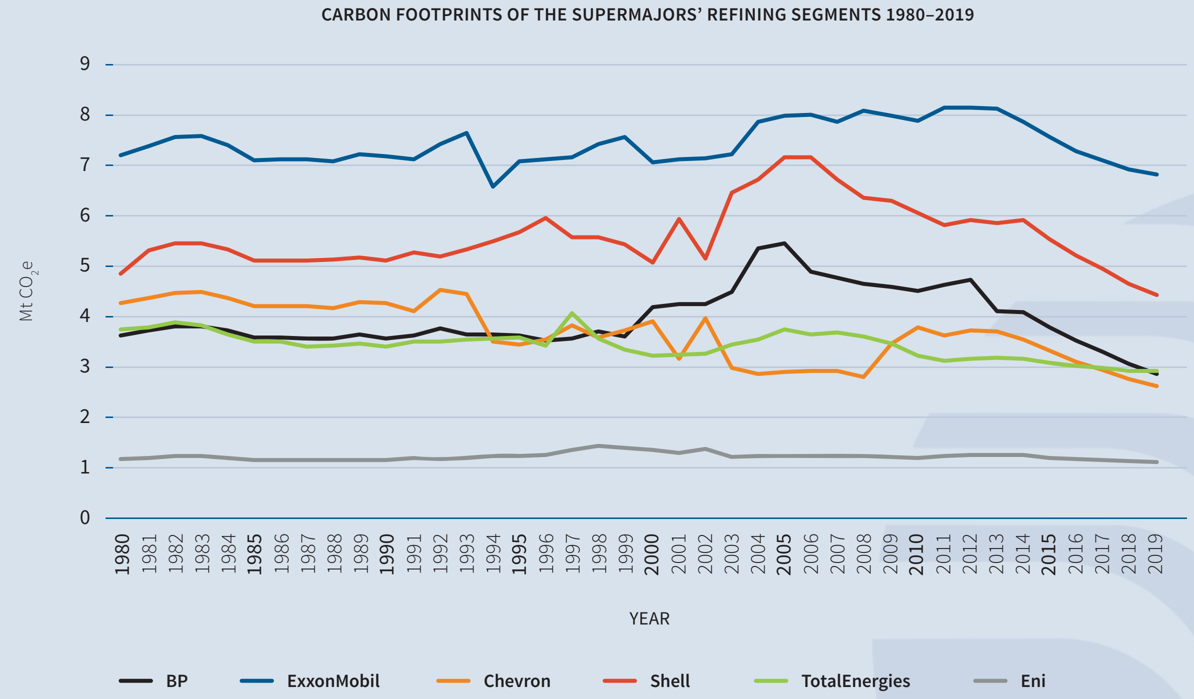
FIGURE 33: SUPERMAJORS' REFINERY OUTPUT 1980–2019



Third, we apply the aforementioned geographic distribution of the supermajors[31] to their refinery output and multiply it to the corresponding country-specific life-cycle GHG emission factors to estimate the carbon footprint of the companies' refining segments over time.

From 1980 to 2019, the refining segment of the supermajors is estimated to account for 101.22 Gt CO_2e released from the 227.52 billion barrels of petroleum products produced by refineries, which accounts for 22.86% of the carbon footprint of the global refining sector during 1980–2019 (see Figure 34).

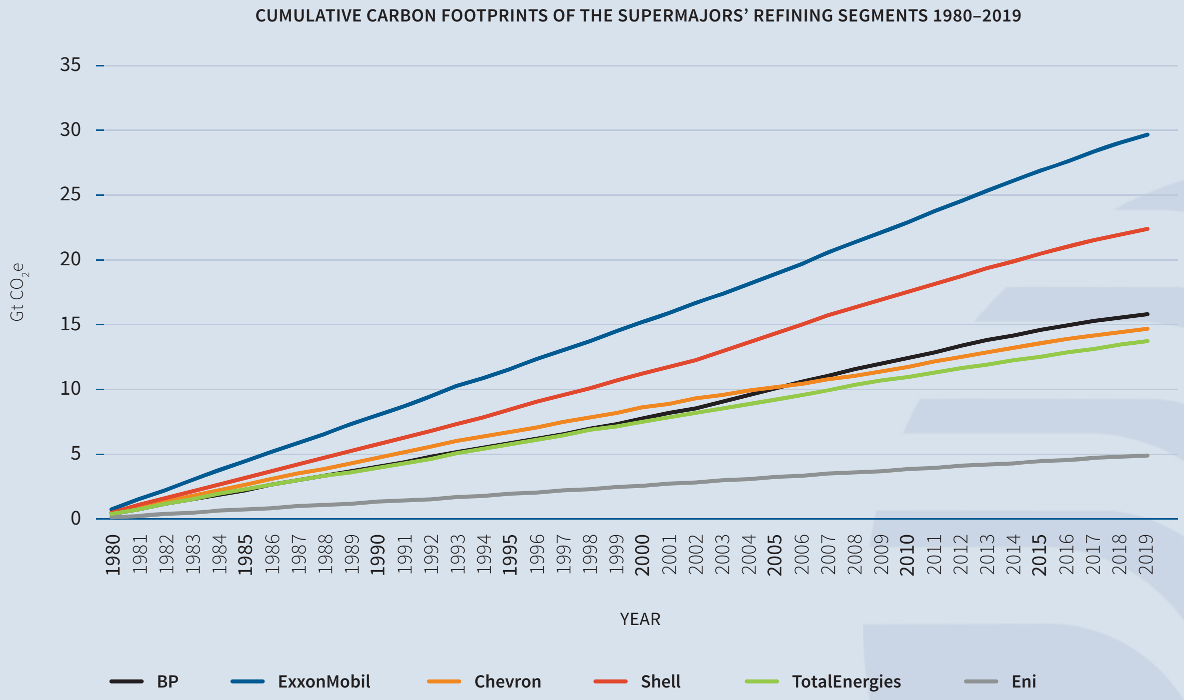
FIGURE 34: ANNUAL AND CUMULATIVE CARBON FOOTPRINTS OF THE SUPERMAJORS' REFINING SEGMENTS 1980–2019



FOOTNOTES

[31] To address the lack of publicly available data, we adopt the same geographic distribution as in the petroleum sales sector (Figures 17, 19, 21, 23, 25, and 27).

FIGURE 34: ANNUAL AND CUMULATIVE CARBON FOOTPRINTS OF THE SUPERMAJORS' REFINING SEGMENTS 1980–2019



4.2.4. Comparison with the Petroleum Products Sales Sector

Compared with the petroleum products sales segment, the refining segment of the supermajors accounts for a smaller proportion of the global carbon footprint (22.86% vs. 35.03%), which reveals that the refining sector is less concentrated. In terms of individual companies, the supermajors' petroleum products sales segments have a larger carbon footprint than their refining segments (see Table 19 and Figures 35 and 36). This difference is aligned with the reality that big oil companies hold bigger market shares of the downstream market than of the refining market.

TABLE 19: CUMULATIVE CARBON FOOTPRINTS AND MARKET SHARES OF SUPERMAJORS

	ESTIMATES BY THE AUTHORS				ESTIMATES BASED ON CLIMATE ACCOUNTABILITY INSTITUTE (2020)
	OIL REFINING[1]		PETROLEUM PRODUCTS SALES[1]		OIL PRODUCTION[2]
SUPERMAJOR	Mt CO_2 e	% OF GLOBAL SECTOR	Mt CO_2 e	% OF GLOBAL SECTOR	Mt CO_2 e
BP	15,827	3.57%	40,394	7.94%	15,027
CHEVRON	14,693	3.32%	28,659	5.64%	13,856
ENI	4,882	1.10%	4,450	0.88%	4,114
EXXONMOBIL	29,710	6.71%	46,187	9.08%	14,724
SHELL	22,389	5.06%	44,444	8.74%	12,105
TOTALENERGIES	13,722	3.10%	13,976	2.75%	7,279
TOTAL	**101,224**	**22.86%**	**178,109**	**35.03%**	**67,105**

Note:

1. The carbon footprints of the supermajors' Oil Refining and Petroleum Products Sales segments and the shares of each company's emissions in the global carbon footprint of the two sectors result from our estimations, based on our life-cycle, supply-chain methodological approach. While the carbon footprints or shares in global emissions may be added up within each sector, they are not meant to be added up across sectors as they overlap.
2. The carbon footprints of the supermajors' Oil Production segments are based on data from Climate Accountability Institute (2020) and on data for 2019 provided by Richard Heede, building on Heede (2014), and employing an upstream-focused methodological approach to estimate the emissions from their extraction-based activities. These carbon footprints are not meant to be directly compared to the ones resulting from our estimation, considering that they result from the application of a different methodology; they are provided here to illustrate that methodological differences affect estimates and to evidence the importance of not only looking into the supermajors' extraction-based activities, but also considering their contribution to emissions from the midstream and downstream levels of the value chain.

FIGURE 35: EMISSIONS FROM THE SUPERMAJORS’ PETROLEUM PRODUCTS SALES SEGMENTS, 1980–2019

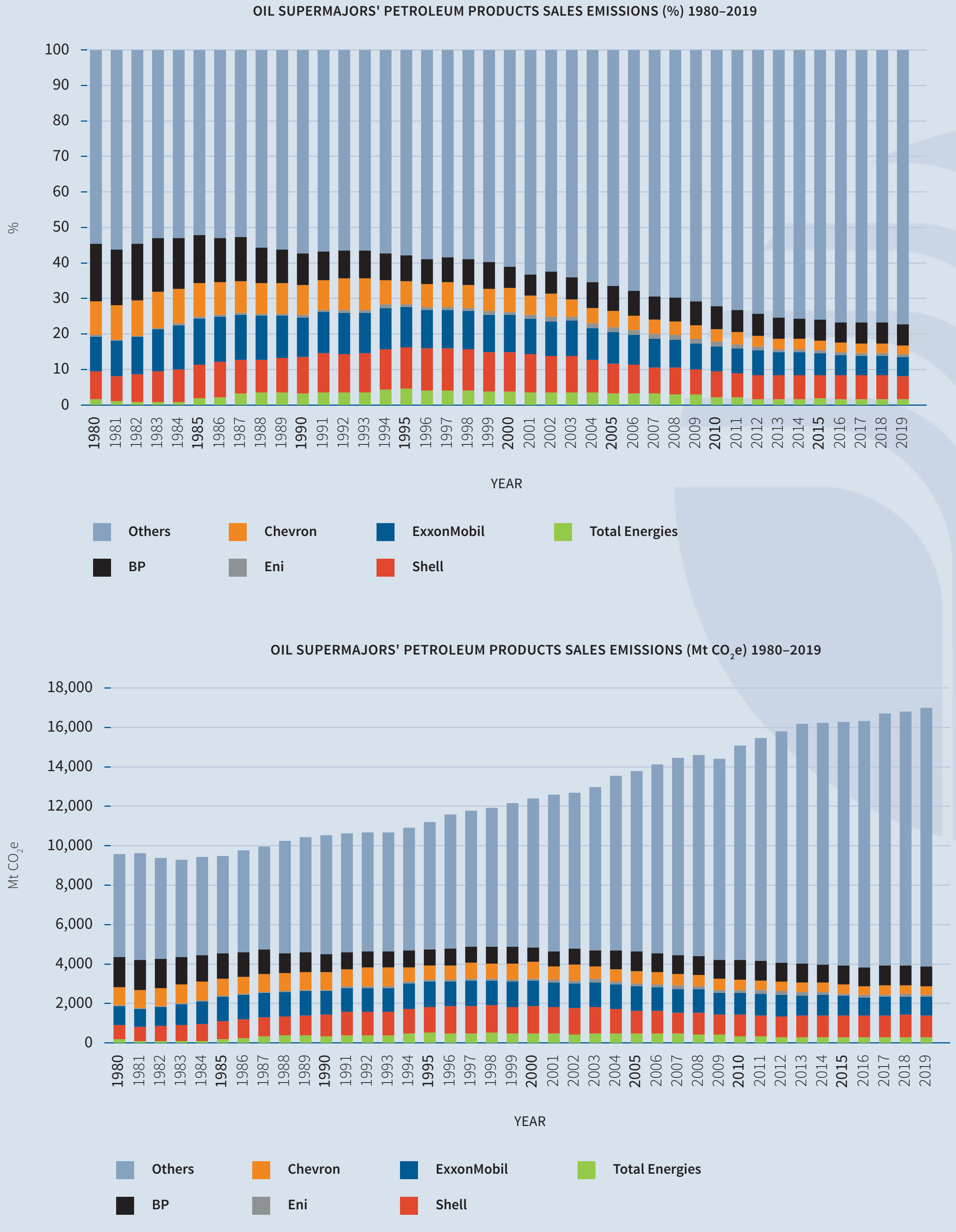
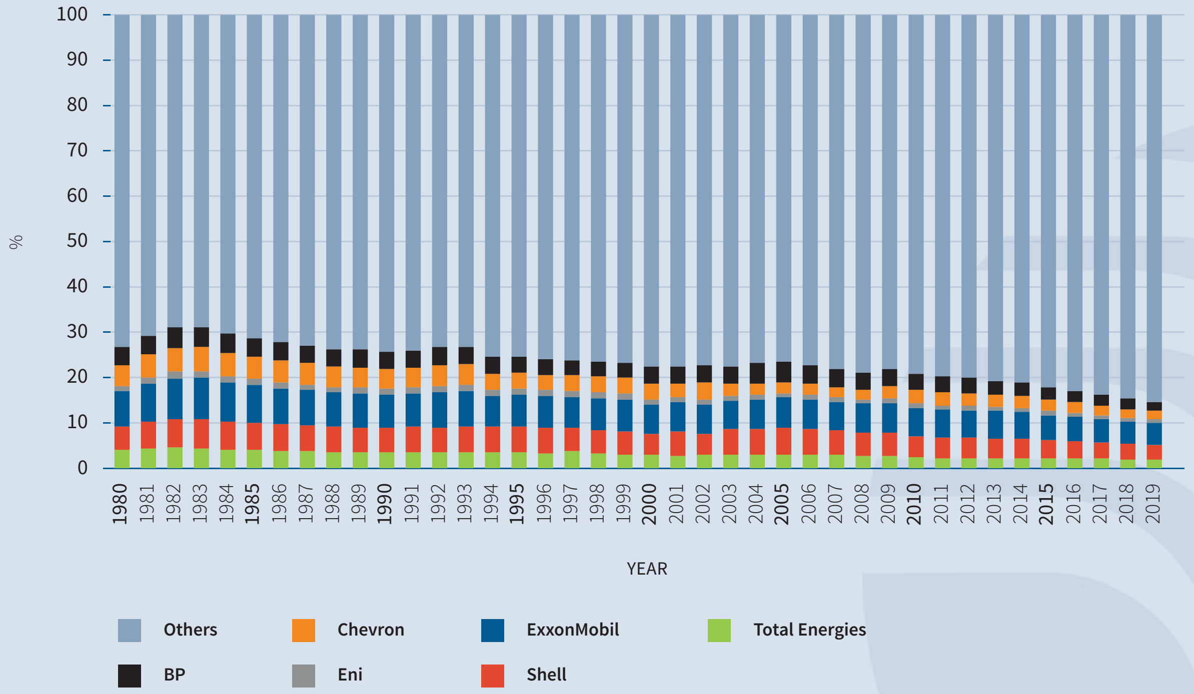
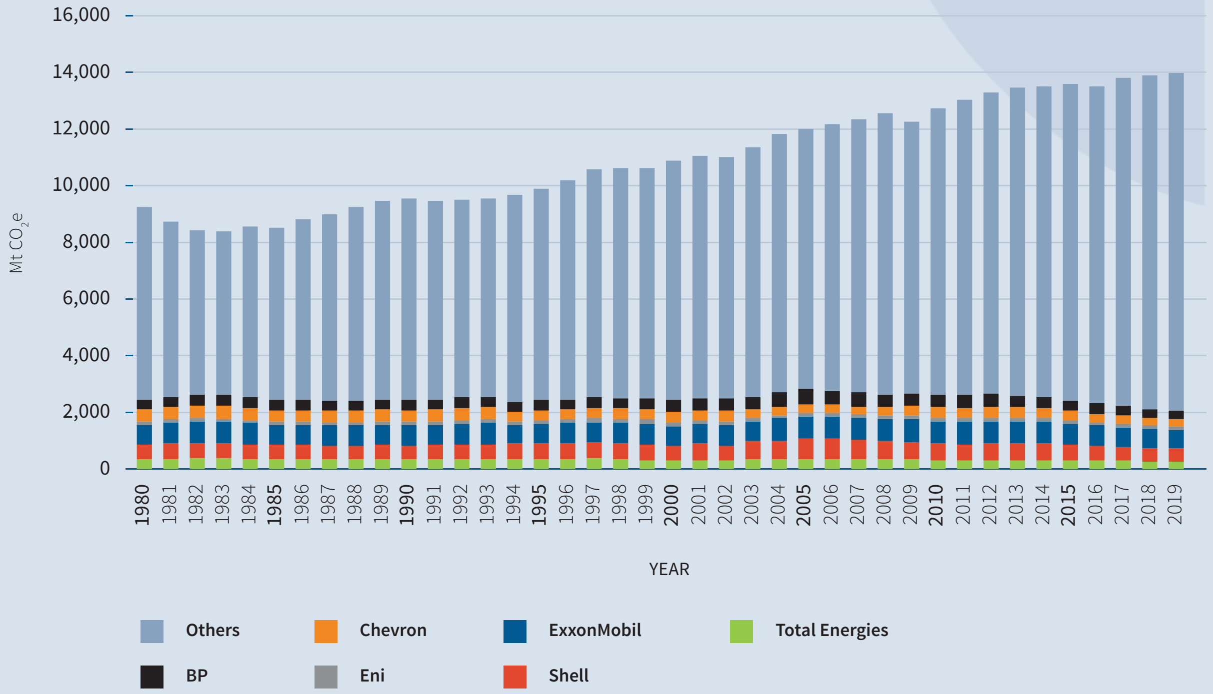


FIGURE 36: EMISSIONS FROM THE SUPERMAJORS' REFINING OIL SEGMENTS, 1980–2019

OIL SUPERMAJORS' REFINING SEGMENTS EMISSIONS (%) 1980–2019



OIL SUPERMAJORS' REFINING SEGMENTS EMISSIONS (Mt CO_2e) 1980–2019

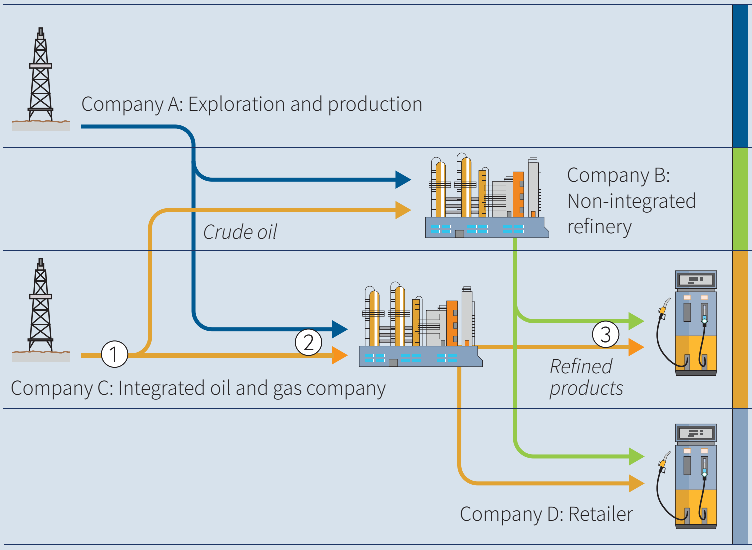


Moreover, while the carbon footprints of the supermajors' refining and sales segments vary, there is a coefficient of variation of 1.43% among the supermajors' carbon intensities in the refining segment and 1.06% among the supermajors' carbon intensities in the sales segment.[32] Both coefficients of variation are much lower than 1, which indicates a narrow difference between the carbon intensities of the supermajors in each segment.

The result is not surprising as the supermajors refine and sell petroleum products originating from crude oil extracted by themselves but also by other companies. For instance, the oil used for more than 50% of Shell's sold products comes from third parties (Shell 2021d). When Shell sells these petroleum products, the carbon embedded in them comes from multiple oil fields associated with different values of API gravity, refinery efficiency, and distribution distance, which also means that the API gravity of Shell's typical oil fields as well as the impact of Shell's refinery efficiency and distribution network is diluted in a portfolio of API gravity, refinery efficiency, and distribution distance values associated with oil coming from other companies (see Figure 37 as an illustration of how value chains mingle).

To understand the contribution of the supermajors to carbon emissions, it is crucial to evaluate them from the angles of different sectors. When evaluating a company's carbon footprint solely from the refining sector, we may omit the emissions of the petroleum products sold by the company but not refined by the company's refinery. When evaluating a company's carbon footprint solely from the petroleum products sales sector, we may omit the emissions of the petroleum products not sold by the company but refined by the company's refinery. While both carbon footprints are not additive, they are both distinctly necessary to understand companies' contribution to fossil fuel emissions. Taking the perspective of the oil refining and petroleum products sales segments also teaches us that companies' value chains are so mingled that, in the current state of data disclosure, differentiating between companies' footprints is a difficult exercise.

FIGURE 37: SIMPLIFIED ILLUSTRATION OF FOUR PETROLEUM COMPANIES WITH DIFFERENT OPERATIONS MINGLING ALONG THE PRODUCT VALUE CHAIN



Company A: An E&P company that produces crude oil and sells it to Refinery B and IO&G Company C.

Company B: A non-integrated refinery that purchases crude oil from E&P Company A and IO&G Company C.

Company C: an IO&G company that produces crude oil and has refinery as well as retail and commercial (marketing) operations. In addition to producing its own crude oil, IO&G Company C purchases crude oil from E&P Company A. IO&G Company C sells retail and commercial products produced by its own refining operations as well as some produced by refinery Company B. IO&G Company C also sells refinery products to retailer Company D.

Company D: a retail operation that purchases products from refinery Company B and IO&C Company C.

Source: *IPIECA (2016).*

FOOTNOTES

[32] For each sector, we calculate the carbon intensity by dividing the total emissions (in Mt CO_2e) by the total volume (in billion barrels) of either oil refined by all refineries or petroleum products sold, as the case may be, from 1980 to 2019. We then calculate the standard deviations of the carbon intensity of the six supermajors in each sector. Finally, we divide each standard deviation by the mean to calculate the coefficient of variation. Coefficients of variation lower than 1 indicate low variability. Coefficients of variation equal to or higher than 1 indicate high variability.

FIGURE 38: ANNUAL CARBON FOOTPRINTS OF THE SUPERMAJORS' REFINING & PETROLEUM PRODUCTS SALES SEGMENTS 1980–2019

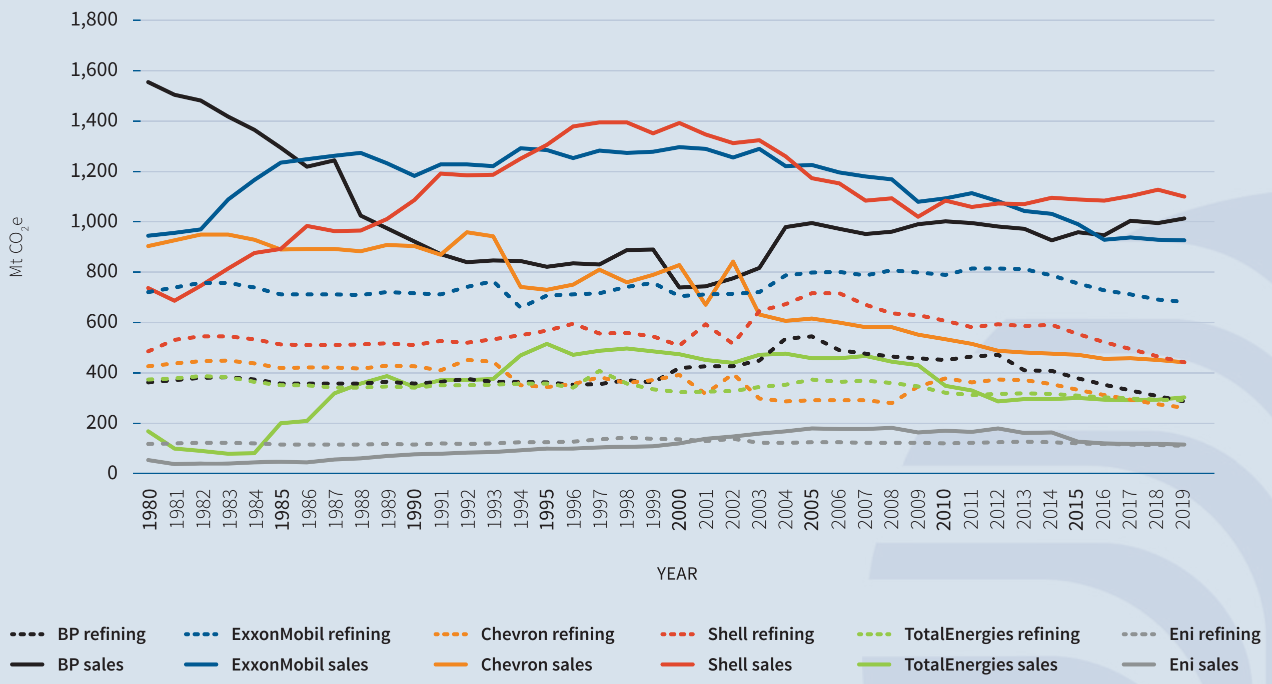
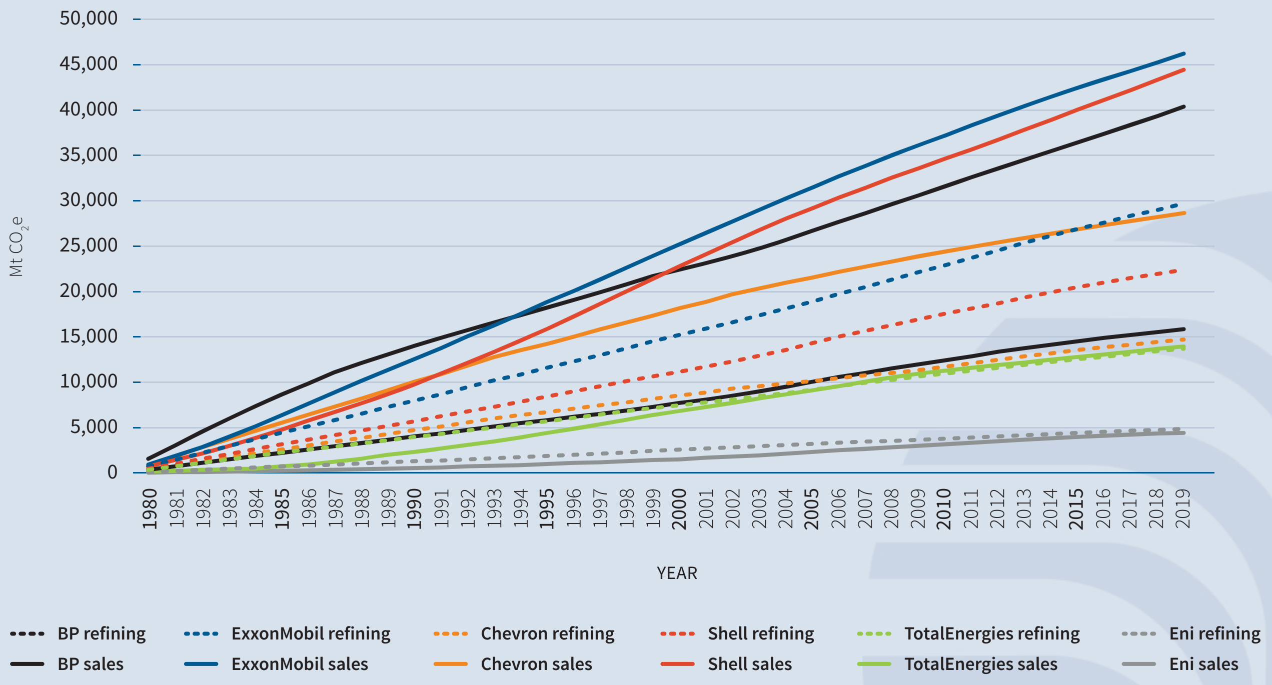


FIGURE 39: CUMULATIVE CARBON FOOTPRINTS OF THE SUPERMAJORS' REFINING & PETROLEUM PRODUCTS SALES SEGMENTS 1980–2019

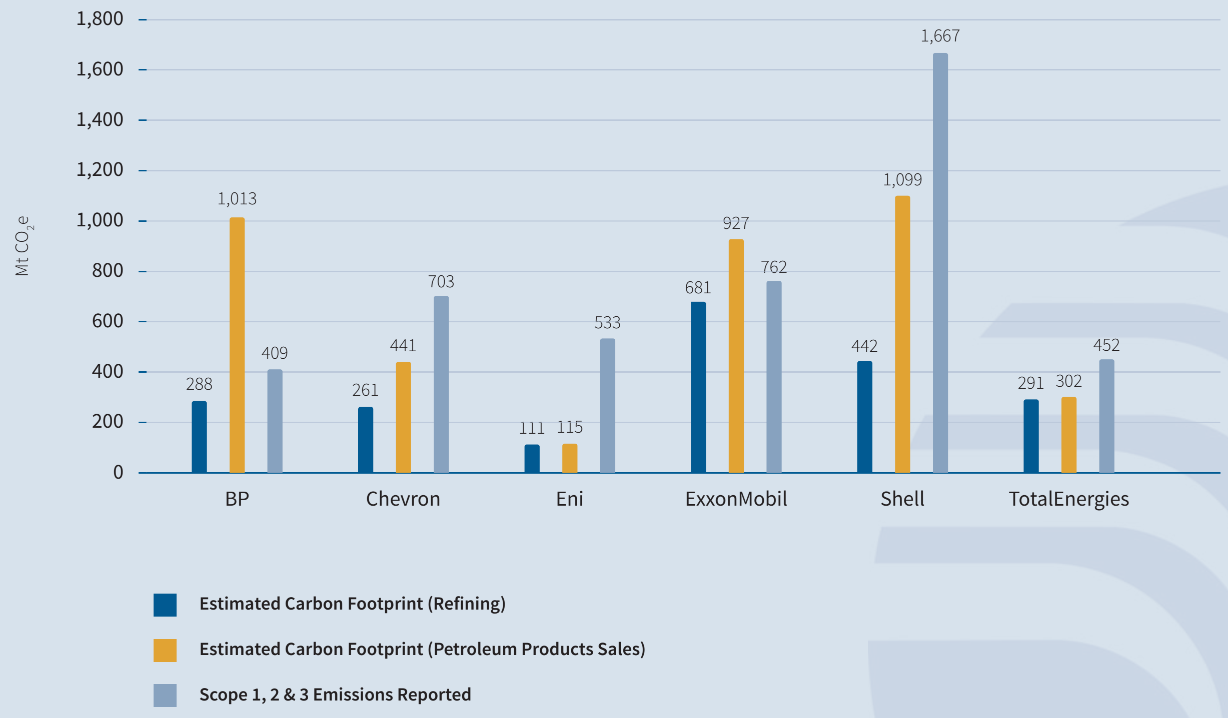


4.3. DIFFERENT EMISSION ACCOUNTING METHODS LEAD TO DIVERGENT RESULTS

Figure 40 shows, for each of the supermajors, our estimates of their cumulative carbon footprints in the refining and petroleum products sales sectors and the sum of their reported scope 1, 2, and 3 emissions. We take a different perspective on scope 1 than companies' reported scopes 1, 2, and 3 (since reported scope 1 is the upstream sector). Even so, scope 3 – category 11 (use of sold products) is the biggest factor contributing to the carbon footprint in both our study and the companies' reports.

The purpose of Figure 40 is not to invite conclusions based on the numerical differences between the carbon footprints reported by the companies and those estimated in our study, but to highlight how different methodological choices can lead to widely divergent results. Company numbers rely on various and not fully transparent reporting boundaries, volume, and emission accounting methodologies, as described below and summarized in Tables 20 and 21.

FIGURE 40: ESTIMATED CARBON FOOTPRINTS VS. REPORTED SCOPE 1, 2, AND 3 EMISSIONS IN 2019[33]



FOOTNOTES

[33] Scope 1, 2, & 3 emissions reported by companies are calculated based on their reported figures in 2019, except for ExxonMobil. ExxonMobil started to report scope 3 emissions from 2020 so we adopt its 2020 scope 3 emissions data as reported data. BP's reported scope 1, 2, & 3 emissions in 2019 are 409 Mt CO$_2$e (BP 2020b); ExxonMobil's reported estimated scope 1, 2, & 3 emission in 2020 is 762 Mt CO$_2$e, which is the sum of the estimated greenhouse emissions 112 Mt CO$_2$e and the estimated scope 3 emissions based on petroleum products sales 650 Mt CO$_2$e (ExxonMobil 2021d); Total Energies' reported scope 1, 2, & 3 emissions in 2019 is 451.5 Mt CO$_2$e (TotalEnergies 2020a); Shell's reported net carbon footprint in 2019 is 1667 Mt CO$_2$e (Royal Dutch Shell 2021d); Chevron's reported scope 1, 2, & 3 emissions in 2019 is 703 Mt CO$_2$e (Chevron 2021b); Eni's reported net GHG lifecycle emissions in 2019 is 533 Mt CO$_2$e (Eni 2020a).

1. Company reporting varies depending on the net volume accounting method used for calculating scope 3, Category 11 (use of products sold). This method can be based on production, sales, or throughput. The production-based method considers the volume of crude oil extracted by the reporting company. The sales-based method takes into account the volume of products sold by the reporting company, which often contain products extracted and refined by third parties. The throughput method is based on the refining throughput of the company, which refers to the volume of crude oil refined (IPIECA 2016). As shown in Table 20, BP and Eni adopt the net volume accounting method based on upstream production (BP 2022; Eni 2020a). However, in its net GHG life-cycle emissions metric, Eni uses the sales method. Shell and TotalEnergies adopt the net volume method based on sales, which only reports the emissions from petroleum products that are sold by the companies, but could be produced and refined by third parties (Shell 2021d; TotalEnergies 2021). ExxonMobil and Chevron have disclosed scope 1, 2, and 3 emissions under the three net volume accounting methods (Chevron 2021b; ExxonMobil 2021d), but ExxonMobil mostly refers to the production method. To facilitate the comparison between companies in Figure 40 above, for Eni, Exxon, and Chevron, we report their sales-based reported figures (BP only provides the production-based method figure). Our estimated carbon footprint for the petroleum products sales sector is calculated based on the sales method in order to also include emissions from petroleum products that are sold by the companies but produced or refined by others (in addition to a company's own value chain). Similarly, our estimated carbon footprint for the oil refining sector is based on the throughput method and also includes emissions from oil sold and extracted by third parties (in addition to a company's own value chain).
2. Companies can report emissions proportional to their equity interest in joint ventures (JVs) (equity method), on a 100% basis when they are operators in JVs (operational control method), or both (IPIECA 2016). For scopes 1 and 2, BP, Shell, and Chevron report according to both methods. In terms of scope 3 emissions, BP reports according to the equity method, Shell reports according to the operational control method, and Chevron reports under both methods (BP 2020b; Shell 2021d; Chevron 2021b). TotalEnergies reports according to both methods for scope 1 but only according to the operational control method for scope 2 emissions; the method for scope 3 emissions is unclear (TotalEnergies 2020a). Eni only reports according to the operational control method for scopes 1 and 2 but according to the equity method for scope 3 (Eni 2020a). ExxonMobil does not appear to disclose both methods separately for any of the scopes; the disclosure method is unclear. In Figure 40 above, when companies offer a choice of methods, we chose the equity method to facilitate comparison between companies. Moreover, our estimated carbon footprints are based on the equity method, since the volumes used—companies' reported sales volume and refining outputs—are based on the equity method. However, the emission factors we use take the whole oil value chain into account,[34] regardless of the ownership or equity interest of the production and refining facilities.
3. BP, ExxonMobil, Chevron, and TotalEnergies only reported Category 11 (use of sold products) in scope 3 emissions. Shell reported Categories 1, 3, and 11, and Eni reported 11 out of 15 categories in scope 3 emissions. Our estimated carbon footprints, while not being scope-based, can be considered to include Categories 1, 3, 5, 9, and 11 (as shown in Tables 17 and 18).
4. Since the supermajors are multi-segmental energy companies, their business does not only include the oil sector but also the gas and biofuel sectors. Thus, for all of them besides ExxonMobil, their reported scope 1, 2, and 3 emissions include emissions from petroleum and non-petroleum products. ExxonMobil consolidates oil and gas products but excludes biofuels from scope 3. Failing to disaggregate the information by type of product hinders the companies' ability to develop tailored decarbonization strategies. Aggregating with biofuels, which may also include biomass-related negative emissions, clouds the picture. Moreover, these emissions rely on petroleum products sales volumes and refinery throughput, whose accounting varies from one company to the other (see Table 21), further obscuring analysis and comparison.
5. Most companies apply API gravity and IPCC emission factors to calculate their emissions; some companies, such as Chevron and Shell, specify that they rely on local reporting methodologies when they can, with no further information. Overall, company reports provide little information on which and how emission factors are used and on the room for uncertainty and inaccuracy.

FOOTNOTES

[34] The life-cycle emission factors take account for all emissions that occurred from oil exploration to final combustion for a barrel of oil regardless of which company is executing the activities..

TABLE 20: COMPANIES' EMISSION REPORTING METHODOLOGIES

SUPERMAJORS	NET VOLUME ACCOUNTING METHODOLOGY FOR CATEGORY 11	REPORTED SCOPE 3 - CATEGORY 11 EMISSIONS WHEN OIL IS PRODUCED/ REFINED BY OTHERS	WHAT JV EMISSIONS ARE BEING REPORTED IN SCOPES 1, 2 AND SCOPES 3	ARE PETROLEUM PRODUCTS CONSOLIDATED WITH NON-PETROLEUM PRODUCTS IN SCOPES 1, 2, 3?	IPIECA SCOPE 3 EMISSIONS CATEGORIES INCLUDED IN REPORTING
EXXONMOBIL	Production method	No	Scopes 1 and 2: 100% operated and pro-rated to equity share. Scope 3: pro-rated to equity share (Participation in Rosneft not considered).	Yes.	Category 11.
Source	*BP 2022.*	*BP 2020b, 4, note e.*	*BP 2020b, 4, notes a, d.*	*BP 2020a, 24, note d.*	*BP 2020b, 4.*
CHEVRON	Reports data in three methods separately: production, throughput, and sales methods.	Depends on the method.	Scopes 1, 2, and 3: 100% operated and pro-rated to equity share.	Yes.	Category 11.
Source	*Chevron 2021b, 4.*	*Chevron 2021b, 15, note 2.*	*Chevron 2021b, 15, note 2.*	*Chevron 2021b, 15, note 2.*	*Chevron 2021b, 16, note 18.*
ENI	Production method. Sales method used for Net GHG Life Cycle Emissions (Scopes not disaggregated).	No (except for GHG Life Cycle Emissions).	Scopes 1 and 2: 100% operated. Scope 3: pro-rated to equity share.	Yes.	Category 1, 2, 3, 4, 5, 6, 7, 10, 11, 12, 14.
Source	*Eni 2020a, 7.*	*Eni 2020a, 7.*	*Eni 2020a, 7.*	*Eni 2020a, 6.*	*Eni 2020a, 6.*
EXXONMOBIL	Reports data in three methods: production (used in most disclosures), throughput (indicated), and sales (indicated).	Depends on the method used (production method is the most used).	Scopes 1 and 2: no separate reporting between 100% operated and pro-rated equity share. Scope 3: unclear	Biofuels are excluded from Scope 3.	Category 11.
Source	*ExxonMobil 2021d, 43.*	*ExxonMobil 2021d, 43.*	*ExxonMobil 2021d, 38.*	*ExxonMobil 2021c.*	*ExxonMobil 2021d, 43.*
SHELL	Sales Method.	Yes.	Scopes 1 and 2: 100% operated and pro-rated to equity share . Scope 3: 100% operated.	Yes.	Category 1, 3, 11.
Source	*Shell 2021d, 93, Scope 3 GHG Emissions, note F.*	*Shell 2021d, 93*	*Shell 2021d, 84.*	*Shell 2021d, 93, Scope 3 GHG Emissions, notes.*	*Shell 2021d, 93.*
TOTALENERGIES	Sales Method.	Yes.	Scopes 1: 100% operated and pro-rated equity to share. Scope 2: 100% operated. Scope 3: unclear.	Yes.	Category 11.
Source	*TotalEnergies 2021, 255, note b.*	*TotalEnergies 2021, 273.*	*TotalEnergies 2020a, 56.*	*TotalEnergies 2021, 255.*	*TotalEnergies 2021, 256.*

TABLE 21: COMPANIES' VOLUME REPORTING METHODOLOGIES

SUPERMAJORS	CLASSIFICATION OF SOLD PETROLEUM PRODUCTS	DO SOLD PETROLEUM PRODUCTS OR REFINERY THROUGHPUT INCLUDE PRODUCTS OR REFINERY THROUGHPUTS FROM EQUITY AFFILIATES?	ADDITIONAL DESCRIPTION OF BOTH PRODUCT VOLUMES AND REFINERY THROUGHPUT
BP	No information about the differentiation of petroleum products.	Refinery throughput "does not include BP's interest in Pan American Energy Group" ; no information on sales volumes.	"Marketing sales include branded and unbranded sales of refined fuel products and lubricants to business-to-business and business-to-consumer customers, including service station dealers, jobbers, airlines, small and large resellers such as hypermarkets, and the military."
Source	-	*BP 2021, 318, Refinery throughputs, note a.*	*BP 2021, 318, Sales volume, note a.*
CHEVRON	Gasoline, Diesel/Gas oil, Jet fuel, Fuel oil, Other	Yes (no further details)	Refinery volumes disclaimer: Includes sales of affiliates.
Source	*Chevron 2021a, 37.*	*Chevron 2021a, 37.*	*Chevron 2021a, 41.*
ENI	Gasoline, Gasoil, Jet fuel/Kerosene, Fuel oil, LPG, Lubricants, Petrochemical, feedstock, Other.	Unclear for sales volumes, for refinery throuput: "includes 20% share in ADNOC Refining".	No further description.
Source	*Eni 2021, 62.*	*Eni 2021, 55.*	*Eni 2021, 62.*
EXXONMOBIL	Gasoline, Naphtha, Heating oils, Kerosines, Diesel oils Aviation fuels, Heavy fuels, Specialty petroleum products.	"Operating statistics include 100 percent of operations of majority-owned subsidiaries; for other companies, crude production, gas, petroleum product and chemical prime product sales include ExxonMobil's ownership percentage and refining throughput includes quantities processed for ExxonMobil."	"Petroleum product and chemical prime product sales data reported net of purchases/sales contracts with the same counterparty."
Source	*ExxonMobil 2021b, 123.*	*ExxonMobil 2021b, 123.*	*ExxonMobil 2021b, 123, note 2.*
SHELL	Gasolines, Kerosines, Gas/Diesel oils, Fuel oil, Other products.	"Reported volumes in 2020 and 2019 include the Shell joint ventures' sales volumes from key countries." "Sales volumes include the Shell share of Raízen's sales volumes."	"Excludes deliveries to other companies under reciprocal sale and purchase arrangements, that are in the nature of exchanges. Sales of condensate and natural gas liquids are included." "Certain contracts are held for trading purposes and reported net rather than gross. The effect in 2020 was a reduction in oil product sales of approximately 1,284,000 b/d (2019: 546,000 b/d; 2018: 458,000 b/d). With effect from January 1, 2020 certain contracts held for trading purposes and reported net for Europe and Asia regions are consolidated in Europe." Refinery processing outturn: "Excludes own use and products acquired for blending purposes."
Source	*Shell 2021c.*	*Shell 2021c, Oil Products sales volumes, notes B, D.*	*Shell 2021c.*
TOTALENERGIES	LPG, Motor gasoline, Avgas and jet fuel, Diesel fuel and heating oils, Fuel oils, Lubricants, Solvents, Bitumen, Other products.	Motor gasoline and jetfuel sales include "TOTAL's share in CEPSA until July 31, 2011 and in TotalErg since October 1, 2010"; Refineries thoughput "include equity share of refineries in which the Group holds a direct or indirect interest".	For product sales: excludes trading and bulk sales; for certain areas in geographical distribution, it is specified that the sales from service stations acquired in 2016 are included.
Source	*TotalEnergies 2020b, 129.*	*TotalEnergies 2020b, 120.*	*TotalEnergies 2020b, 129.*

CONCLUSION

The design of our life-cycle model has addressed several limitations of the current literature:

1. To address the lack of a method to estimate emissions from the whole oil value chain, we build our estimation model on three commonly used models in the upstream, midstream, and downstream sectors and incorporate a range of stages within the oil value chain defined by government agencies, industry associations, and other stakeholders.
2. To reflect the differences in emission factors resulting from different geographies and technology changes, we estimate country-specific emission factors.
3. We validate the statistical significance of API gravity to emissions and apply the decision-tree model to calculate non-linear estimations of upstream emissions and the production rates of the refining sector, which we later use to estimate downstream emissions.

4. To create a time series of country-specific emission factors, we examine the changes in default emission factors and key parameters over time.

Applying our life-cycle model to refinery output and data on the sales of petroleum products, both by each supermajor and globally, we separately estimate their carbon footprints for both the refining and petroleum products sales sectors. These carbon footprints are not meant to be added up as they overlap.

The petroleum products sales sector sold a total of 1,128.06 billion barrels of petroleum products from 1980 to 2019, leading to emissions of 508.43 Gt CO_2e, nearly doubling its annual carbon footprint over the period. The supermajors jointly account for 35.03% of the cumulative carbon footprint of the sector from 1980 to 2019, which reflects the market concentration in the sector.

The oil refining sector refined a total of 984.45 billion barrels of crude oil from 1980 to 2019, leading to emissions of 442.84 Gt CO_2e, with a 51.08% increase in its annual carbon footprint over the period. The supermajors jointly account for 22.86% of the cumulative carbon footprint of sector from 1980 to 2018, which reflects a lower but still significant market concentration in the refining sector.

The report also scrutinizes companies' accounting methods to report emissions and concludes that company numbers rely on various and not fully transparent reporting boundaries, volume, and emission accounting methodologies. Most problematic is that most supermajors fail to report scope 3 emissions comprehensively, and in any event, there is a lack of time-series data of scope 3 emissions. In addition, the volume and emission accounting method might underestimate emissions in three ways: by omitting the emissions of third parties in the company's value chain (e.g. when a company sells petroleum products produced and refined by other companies or when it refines products later sold by other companies), playing with boundaries, or omitting data from non-operated JVs.

The six supermajors own a sizable share of the oil refining and petroleum products sales sectors. Focusing only on their extractive activities conceals the depth of their hold on oil value chains. This paper sheds light on their contribution to emissions from the midstream and downstream levels of the value chain.

LIMITATIONS AND FURTHER RESEARCH

There are several limitations in our estimation.

First, there is the limitation related to data availability. To address the lack of publicly available data at the oil-field level, we trained our machine-learning model based on the data characterizing the 71 oil fields of the OCI sample.[35] The limited sample could lead to bias in our estimated results. Even though we used a non-linear machine learning model to minimize the estimation errors, we could achieve more robust results if we could derive the estimation model using a larger dataset.

FOOTNOTES

[35] The 71 oil fields account for 9.3% of global crude oil production (as of 2015 data).

When we estimated the time-series change of API gravity, sulfur content, and VFF emission intensities, we applied the evolution of data in the United States—the largest oil producer and consumer—to other countries to address the lack of data for other countries. This omits the heterogeneity of countries. When estimating emissions from transporting from oil fields to refineries, we assumed the same emission factor for all countries within each region. When estimating transport emissions from refineries to sales market, we assumed a constant transportation route for all transportation modes except for ocean tankers since no study or database delivers geography-specific data for the routes of other transportation modes used in the oil industry. When we estimated the carbon footprints of the supermajors, we assumed constant geographic distribution over time and between the refinery and petroleum sales segments. We also used constant production growth over the years for those companies for which we did not have public data in the corresponding years, typically in the 1980s. The default parameters used in the models are from the GREET model simulation and have no significant changes over time, which may not accurately reflect the application of cleaner technology in recent years. The petroleum product sales reported in company reports include the petroleum products that are refined from both crude oil and gas, which may result in the overestimation of carbon footprints of petroleum products refined from crude oil. To address the lack of publicly available refinery data for Eld Aquitaine, ARCO, Gulf Oil Tenneco, and Unocal in the Oil & Gas Journal, we could not adjust the M&A effect for those acquired companies when estimating the carbon footprints for the refining sector.

Second, while we eliminated the risk of double-counting between the stages of oil value chains, there was one specific point where we could not avoid it. When estimating the time-series upstream emission factors by considering the aging of oil fields and the fluctuation of VFF emission intensity over time. Indeed, the flaring intensity due to oil field aging is reflected in both datasets, and there is no publicly available research to quantify the variation of flaring emission intensity due to oil aging.

The data limitations could be addressed in future studies. First, we can re-train the machine learning model based on a larger (or, preferably, universal) dataset of oil fields as more data becomes available. Future studies should also consider the potential effects of those constant assumptions in the estimation models; for example, how the heterogeneity of countries in terms of oil field aging, oil transportation routes, and environmental policies curbing flaring affect countries' actual time-series emission factors. By collecting more data on countries other than the United States, our estimation of the time series of country-specific emission factors could potentially be improved.

These limitations attest to the lack of data transparency and standardized carbon accounting at both country and corporate level, which prevents informed decision-making on those holding the levers of influence on companies: investors, consumers, and policymakers. Without consistent and transparent emissions accounting, companies' net-zero commitment and target settings are meaningless. To address these limitations, the Coalition on Material Emissions Transparency (COMET), supported by the secretariat of the United Nations Framework Convention on Climate Change (UNFCCC), will create a harmonized greenhouse gas calculation framework applicable to all mineral and industrial supply chains.

REFERENCES

Abella. Jessica P., Kavan Motazedi, and Joule A. Bergerson. 2015. *Petroleum Refinery Life Cycle Inventory Model (PRELIM) v1. 0: User Guide and Technical Documentation*. Calgary: University of Calgary, March 2015. https://www.ucalgary.ca/sites/default/files/teams/477/prelim-v1-0-documentation.pdf.

Alexander, Lisa V. 2016. “Global Observed Long-Term Changes in Temperature and Precipitation Extremes: A Review of Progress and Limitations in IPCC Assessments and Beyond.” *Weather and Climate Extremes* 11 (2016): 4–16, https://doi.org/10.1016/j.wace.2015.10.007.

Ali, Umar. 2019. “Top Ten Companies by Oil Production,” *Offshore Technology*, May 14, 2019, https://www.offshore-technology.com/features/companies-by-oil-production.

Banerjee, Shayan and Perrine Toledano. 2016. *A Policy Framework to Approach The Use Of Associated Petroleum Gas*. New York: Columbia Center on Sustainable Investment (CCSI). https://ccsi.columbia.edu/sites/default/files/content/docs/our%20focus/A-policy-framework-for-the-use-of-APG-July-2016-CCSI.pdf.

Bhatia, Pankaj, Cynthia Cummis, David Rich, Laura Draucker, Holly Lahd, and Andrea Brown. 2011. *Greenhouse Gas Protocol Corporate Value Chain (Scope 3) Accounting and Reporting Standard*. Washington DC: World Resources Institute. https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporing-Standard_041613_2.pdf.

Blanco, Christian, Felipe Caro, and Charles J. Corbett. 2016. “The State of Supply Chain Carbon Footprinting: Analysis of CDP Disclosures by US Firms.” *Journal of Cleaner Production* 135 (2016): 1189–1197. https://doi.org/10.1016/j.jclepro.2016.06.132.

Bloomberg LP. 2021a. Financial Analysis for BP PLC 1 December 31, 2008–December 31, 2020. May 15, 2021.

Bloomberg LP. 2021b. Financial Analysis for ExxonMobil December 31, 2000–December 31, 2020. May 9, 2021.

BP. 2020a. *Energy with Purpose: BP Sustainability Report 2019*. London: BP p.l.c., March 2020. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/sustainability/group-reports/bp-sustainability-report-2019.pdf.

BP. 2020b. *ESG Datasheet 2019*. London: BP p.l.c., March 2020. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/sustainability/bp-esg-datasheet-2019.pdf.

BP. 2020c. *Statistical Review of World Energy 2020*. London: BP p.l.c., June 2020. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf.

BP. 2021. *Performing while Transforming from IOC to IEC: BP Annual Report and Form 20-F 2020*. London: BP p.l.c. https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/investors/bp-annual-report-and-form-20f-2020.pdf.

BP. 2022. “GHG Emissions,” GHG emissions | Sustainability | Home. Accessed January 2022. https://www.bp.com/en/global/corporate/sustainability/getting-to-net-zero/ghg-emissions.html

Brandt, Adam R. 2011. “Oil Depletion and the Energy Efficiency of Oil Production: The Case of California.” *Sustainability* 3, no. 10 (2011): 1833–1854. https://doi.org/10.3390/su3101833.

Burklin, C. E. 1977. *Revision of Emission Factors for Petroleum Refining*. Research Triangle Park: EPA Office of Air Waste Management, Office of Air Quality Planning and Standards, October 1977. https://nepis.epa.gov/Exe/ZyNET.exe/91010CRI.txt?ZyActionD=ZyDocument&Client=EPA&Index=1976%20Thru%201980&Docs=&Query=&Time=&EndTime=&SearchMethod=1&TocRestrict=n&Toc=&TocEntry=&QField=&QFieldYear=&QFieldMonth=&QFieldDay=&UseQField=&IntQFieldOp=0&ExtQFieldOp=0&XmlQuery=&File=D%3A%5CZYFILES%5CINDEX%20DATA%5C76THRU80%5CTXT%5C00000021%5C91010CRI.txt&User=ANONYMOUS&Password=anonymous&SortMethod=h%7C-&MaximumDocuments=1&FuzzyDegree=0&ImageQuality=r75g8/r75g8/x150y150g16/i425&Display=hpfr&DefSeekPage=x&SearchBack=ZyActionL&Back=ZyActionS&BackDesc=Results%20page&MaximumPages=1&ZyEntry=2.

Cai, Hao, Xinyi Wang, Jarod C. Kelly, and Michael Wang. 2021. *Building Life-Cycle Analysis with the GREET Building Module: Methodology, Data, and Case Studies No. ANL/ESD-21/13*. Argonne: Argonne National Laboratory, October 2021. https://doi.org/10.2172/1823607.

Capuano, Linda. 2018. *International Energy Outlook 2018 (IEO2018)*. Washington DC: US Energy Information Administration (EIA), July 2018. https://www.eia.gov/pressroom/presentations/capuano_07242018.pdf.

Carpenter, R. G. 1960. “Principles and Procedures of Statistics, with Special Reference to the Biological Sciences,” *The Eugenics Review* 52, no. 3 (1960): 172–173. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2972823.

Chevron. 2011. *2010 Annual Report*. San Ramon: Chevron Corporation. https://www.annualreports.com/HostedData/AnnualReportArchive/c/NYSE_CVX_2010.pdf.

Chevron. 2016. *2015 Annual Report*. San Ramon: Chevron Corporation. https://www.chevron.com/-/media/chevron/annual-report/2015/2015-annual-report.pdf.

Chevron. 2020. *2019 Performance Data*. San Ramon: Chevron Corporation. https://www.chevron.com/-/media/shared-media/documents/2019-sustainabilty-performance-data.pdf.

Chevron. 2021a. *2020 Annual Report*. San Ramon: Chevron Corporation. https://www.chevron.com/-/media/chevron/annual-report/2020/documents/2020-Annual-Report.pdf.

Chevron. 2021b. *2020 Performance Data*. San Ramon: Chevron Corporation. https://www.chevron.com/-/media/shared-media/documents/2020-sustainabilty-performance-data.pdf.

Chevron. 2021c. *2020 Supplement to the Annual Report*. San Ramon: Chevron Corporation. https://www.chevron.com/-/media/shared-media/documents/2020-chevron-annual-report-supplement.pdf.

Climate Accountability Institute. 2020. “Carbon Majors 2018 Data Set.” December 2020. https://climateaccountability.org/carbonmajors_dataset2020.html.

CSIMarket. 2021. “Chevron Inventory Turnover Ratio (COS).” Accessed December 8, 2021. https://csimarket.com/stocks/singleEfficiencyit.php?code=CVX.

CSP Daily News. 2020. “Oil Price Information Service: FUELS 50.” May 26, 2020. https://www.cspdailynews.com/fuels-50-2020.

Dahe, Qin and Thomas Stocker. 2014. “Highlights of the IPCC Working Group I Fifth Assessment Report.” *Advances in Climate Change Research* 10, no. 1 (2014): 1–6, http://www.climatechange.cn/EN/Y2014/V10/I1/1.

Edenhofer, Ottmar, Ramón Pichs-Madruga, Mundial Youba Sokona, Jan C. Minx, Ellie Farahani, Susanne Kadner, Kristin Seyboth, Anna Adler, Ina Baum, Steffen Brunner, Patrick Eickemeier, Benjamin Kriemann, Jussi Savolainen, Steffen Schlömer, Christoph von Stechow, and Timm Zwickel. 2014. Climate Change 2014 Mitigation of *Climate Change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. New York: Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_frontmatter.pdf.

El-Houjeiri, Hassan M., Mohammad S. Masnadi, Kourosh Vafi, James Duffy, and Adam R. Brandt. 2017. *Oil Production Greenhouse Gas Emissions Estimator OPGEE v2.0 User Guide & Technical Documentation*. Sacramento: California Environmental Protection Agency, Air Resources Board, June 2017. https://pangea.stanford.edu/departments/ere/dropbox/EAO/OPGEE/OPGEE_documentation_v2.0.pdf.

Eni. 2012. *Fact Book 2011*. Rome: Eni S.p.A. 2012). https://www.eni.com/assets/documents/documents-en/Fact-book-2011-eng.pdf.

Eni. 2015. *Fact Book 2014*. Rome: Eni S.p.A. https://www.eni.com/assets/documents/documents-en/fact-book-2014-eng.pdf.

Eni. 2018. *Fact Book 2017*. Rome: Eni S.p.A. https://www.eni.com/assets/documents/documents-en/Fact-Book-2017-eng.pdf

Eni. 2020a. *Eni GHG Emissions Statement 2019*. Rome: Eni S.p.A. https://www.eni.com/assets/documents/eng/just-transition/2020/Eni-GHG-Reasonable-Assurance-Statement-2019.pdf.

Eni. 2020b. *Executive Summary: Eni for 2020*. Rome: Eni S.p.A. https://www.eni.com/assets/documents/eng/just-transition/2020/Eni-for-2020-Executive-Summary-eng.pdf.

Eni. 2021. *Fact Book 2020*. Rome: Eni S.p.A.. https://www.eni.com/assets/documents/eng/reports/2020/Fact-Book-2020-eng.pdf.

Eurostat. 2021. “Oil and Petroleum Products – A Statistical Overview.” August, 2021. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Oil_and_petroleum_products_-_a_statistical_overview#Use_of_petroleum_products.

ExxonMobil. 2005. *2004 Financial and Operating Review*. Irving: Exxon Mobil Corporation. https://www.sec.gov/Archives/edgar/data/34088/000095013405005336/d23132exv99.htm.

ExxonMobil. 2010. *2009 Financial and Operating Review*. Irving: Exxon Mobil Corporation. http://media.corporate-ir.net/media_files/irol/11/115024/XOM_2009F&O.pdf.

ExxonMobil. 2014. *2013 Financial and Operating Review*. Irving: Exxon Mobil Corporation. https://corporate.exxonmobil.com/-/media/Global/Files/investor-relations/analyst-meetings/2013_ExxonMobil_Financial_and_Operating_Review.pdf

ExxonMobil. 2018. *2017 Financial and Operating Review*. Irving: Exxon Mobil Corporation. https://corporate.exxonmobil.com/-/media/Global/Files/annual-report/2017-Financial-and-Operating-Review.pdf.

ExxonMobil. 2021a. *2020 Financial and Operating Data*. Irving: Exxon Mobil Corporation. https://corporate.exxonmobil.com/-/media/Global/Files/annual-report/2020-Financial-and-Operating-Data.pdf.

ExxonMobil. 2021b. *ExxonMobil 2020 Annual Report* (Irving: Exxon Mobil Corporation. https://corporate.exxonmobil.com/-/media/Global/Files/investor-relations/annual-meeting-materials/annual-report-summaries/2020-Annual-Report.pdf.

ExxonMobil. 2021c. *Scope 3 Emissions: Energy and Carbon Summary*. Irving: Exxon Mobil Corporation. https://corporate.exxonmobil.com/Sustainability/Energy-and-Carbon-Summary/Scope-3-emissions.

ExxonMobil. 2021d. *Updated 2021 Energy and Carbon Summary*. Irving: Exxon Mobil Corporation. https://corporate.exxonmobil.com/-/media/global/files/energy-and-carbon-summary/energy-and-carbon-summary.pdf.

Fitzgibbon, Tim. 2020. “McKinsey Refinery Capacity Database.” *Energy Insights by McKinsey*. https://www.mckinseyenergyinsights.com/resources/refinery-reference-desk/refining-companies.

Gary, James H., James H. Handwerk, Mark J. Kaiser, and David Geddes. 2007. *Petroleum Refining: Technology and Economics*. Boca Raton: CRC Press. https://www.taylorfrancis.com/chapters/mono/10.4324/9780203907924-6/introduction-james-gary-james-handwerk-mark-kaiser-david-geddes?context=ubx&refId=c3d783f4-9a73-4159-af5a-6210834a68c8.

Gavenas, Ekaterina, Knut Einar Rosendahl, and Terje Skjerpen. 2015. “CO_2-Emissions Form Norwegian Oil and Gas Extraction.” Discussion Papers Statistics Norway Research Department No. 806. Oslo: Statistics Norway, April 2015. https://www.econstor.eu/bitstream/10419/192788/1/dp806.pdf.

Gillenwater, Michael. 2015. “GHG Protocol tool for stationary combustion version 4.1,” World Resources Institute, May 2015. https://ghgprotocol.org/sites/default/files/Stationary_Combustion_Guidance_final_1.pdf.

Global Carbon Project. 2021. “Supplemental Data of Global Carbon Budget 2021 (Version 1.0) [Data set].” https://doi.org/10.18160/gcp-2021.

Gordon, Deborah, Adam R. Brandt, Joule Bergerson, and Jon Koomey. 2015. *Know Your Oil: Creating a Global Oil-Climate Index*. Washington DC: Carnegie Endowment for International Peace. https://carnegieendowment.org/2015/03/11/know-your-oil-creating-global-oil-climate-index-pub-59285.

Gordon, Deborah. 2016. “Oil Products Emissions Module (OPEM).” http://oci.carnegieendowment.org/assets/OPEM1.0.xlsx.

Greene, Suzanne and Alan Lewis. 2019. *Global Logistics Emissions Council Framework for Logistics Emissions Accounting and Reporting*. Amsterdam: Smart Freight Centre. https://www.feport.eu/images/downloads/glec-framework-20.pdf.

Greene, Suzanne, Haiying Jia, and Gabriela Rubio-Domingo. 2020. “Well-to-tank Carbon Emissions from Crude Oil Maritime Transportation.” *Transportation Research Part D: Transport and Environment* 88 (2020): 102587, https://doi.org/10.1016/j.trd.2020.102587.

Heede, Richard. 2014. “Tracing Anthropogenic Carbon Dioxide and Methane Emissions to Fossil Fuel and Cement Producers, 1854–2010.” *Climatic Change* 122, no. 1 (2014): 229–241, https://doi.org/10.1007/s10584-013-0986-y.

Hertwich, Edgar G. and Richard Wood. 2018. “The Growing Importance of Scope 3 Greenhouse Gas Emissions from Iindustry.” *Environmental Research Letters* 13, no. 10 (2018): 104013. https://iopscience.iop.org/article/10.1088/1748-9326/aae19a.

International Association of Oil & Gas Producers (IOGP). 2016. *Environmental Performance Indicators – 2016 Data*. London: IOGP. https://www.iogp.org/bookstore/product/environmental-performance-indicators-2016-data.

International Energy Agency (IEA). 2020. *World Energy Balances 2020 Edition: Database Documentation*. Paris: IEA. https://iea.blob.core.windows.net/assets/4f314df4-8c60-4e48-9f36-bfea3d2b7fd5/WorldBAL_2020_Documentation.pdf.

International Petroleum Industry Environmental Conservation Association (IPIECA). 2011. *Petroleum Industry Guidelines for Reporting Greenhouse Gas Emissions: 2nd edition*. London: IPIECA. https://www.ipieca.org/resources/good-practice/petroleum-industry-guidelines-for-reporting-greenhouse-gas-emissions-2nd-edition.

International Petroleum Industry Environmental Conservation Association (IPIECA). 2016. *Estimating Petroleum Industry Value Chain (Scope 3) Greenhouse Gas Emissions. Overview of Methodologies*. London: IPIECA. https://www.ipieca.org/resources/good-practice/estimating-petroleum-industry-value-chain-scope-3-greenhouse-gas-emissions-overview-of-methodologies.

International Petroleum Industry Environmental Conservation Association (IPIECA). 2020. *Sustainability Reporting Guidance for the Oil and Gas Industry, 4th Edition*. London: IPIECA. https://www.ipieca.org/media/5115/ipieca_sustainability-guide-2020.pdf.

Jing, Liang, Hassan M. El-Houjeiri, Jean-Christophe Monfort, Adam R. Brandt, Mohammad S. Masnadi, Deborah Gordon, and Joule A. Bergerson. 2020. “Carbon Intensity of Global Crude Oil Refining and Mitigation Potential.” *Nature Climate Change* 10, no. 6 (2020): 526–532. https://www.nature.com/articles/s41558-020-0775-3.

Lelieveld, J., K. Klingmüller, A. Pozzer, R. T. Burnett, A. Haines, and V. Ramanathan. 2019. “Effects of Fossil Fuel and Total Anthropogenic Emission Removal on Public Health and Climate,” *Proceedings of the National Academy of Sciences* 116, no. 15 (2019): 7192-7197, https://doi.org/10.1073/pnas.1819989116.

Liu, Ke, Chunshan Song, and Velu Subramani. 2009. *Hydrogen and Syngas Production and Purification Technologies*. Hoboken: John Wiley & Sons. https://doi.org/10.1002/9780470561256.

Manning, Francis and Richard Thompson. 1995. *Oilfield Processing of Petroleum: Crude Oil*. Tulsa: PennWell Books.

Masnadi, Mohammad S., and Adam R. Brandt. 2017. “Climate Impacts of Oil Extraction Increase Significantly with Oilfield Age,” *Nature Climate Change* 7, no. 8 (2017): 551–556, https://doi.org/10.1038/nclimate3347.

Masnadi, Mohammad S., Hassan M. El-Houjeiri, Dominik Schunack, Yunpo Li, Jacob G. Englander, Alhassan Badahdah, Jean-Christophe Monfort, James E. Anderson, Timothy J. Wallington, Joule A. Bergerson, Deborah Gordon, Jonathan Koomey, Steven Przesmitzki, Inês L. Azevedo, Xiaotao T. Bi, James E. Duffy, Garvin A. Heath, Gregory A. Keoleian, Christophe McGlade, D. Nathan Meehan, Sonia Yeh, Fengqi You, Michael Wang, and Adam R. Brandt. 2018. “Global Carbon Intensity of Crude Oil Production,” *Science* 361, no. 6405 (2018): 851–853, https://www.science.org/doi/10.1126/science.aar6859.

Math Pro. 2011. “An Introduction to Petroleum Refining and the Production of Ultra Low Sulfur Gasoline and Diesel Fuel.” October 24, 2011. https://theicct.org/sites/default/files/publications/ICCT05_Refining_Tutorial_FINAL_R1.pdf.

Nelson, Thomas P. 2013. “An Examination of Historical Air Pollutant Emissions from US Petroleum Refineries.” *Environmental Progress & Sustainable Energy* 32, no. 2 (2013): 425–432, https://doi.org/10.1002/ep.11713.

Oil & Gas Journal. *Refinery Report*, 2019.

Oil & Gas Journal. *Worldwide Oil Field Production Survey*, 2010.

OilNow. 2017. “The Super-Majors…What and Who Are They?” Updated August 29. 2017. https://oilnow.gy/uncategorized/the-super-majors-what-and-who-are-they.

Pedregosa, Fabian, Gaël Varoquaux, Alexandre Gramfort, Vincent Michel, Bertrand Thirion, Olivier Grisel, and Mathieu Blondel. 2011. “Scikit-learn: Machine Learning in Python.” *The Journal of Machine Learning Research* 12 (2011): 2825–2830, https://www.jmlr.org/papers/volume12/pedregosa11a/pedregosa11a.pdf.

Riva, Joseph P. and Gordon I. Atwater. 2016. “Heavy Oil and Tar Sand.” *Encyclopedia Britannica*, October 21, 2016. https://www.britannica.com/science/heavy-oil.

Ruh, Ernest. L., James J. Moran, and Robert D. Thompson. 1959. “Measurement Problems in the Instrument and Laboratory Apparatus Fields.” in *Systems of Units: National and International Aspects*. Washington DC: American Association for the Advancement of Science.

Sampson, Anthony. 1976. *The Seven Sisters: The Great Oil Companies and the World They Shaped*. New York: Viking Press. https://doi.org/10.1177/000271627642500117.

Shell. 2012. *Investors’ Handbook 2007–2011*. The Hague: Royal Dutch Shell PLC. https://reports.shell.com/investors-handbook/2011/servicepages/welcome.html.

Shell. 2015. *Investors’ Handbook 2010–2014*. The Hague: Royal Dutch Shell PLC. https://reports.shell.com/investors-handbook/2014/servicepages/welcome.html.

Shell. 2020. *Investors’ Handbook 2015–2019*. The Hague: Royal Dutch Shell PLC. https://reports.shell.com/investors-handbook/2019.

Shell. 2021a. “Greenhouse Gas Emissions.” https://www.shell.com/sustainability/sustainability-reporting-and-performance-data/performance-data/greenhouse-gas-emissions.html.

Shell. 2021b. *Greenhouse Gas and Energy Data: Shell Sustainability Report 2020*. The Hague: Royal Dutch Shell PLC. https://reports.shell.com/sustainability-report/2020/our-performance-data/greenhouse-gas-and-energy-data.html.

Shell. 2021c. *Shell Annual Report 2020: Oil Products Data Tables*. The Hague: Royal Dutch Shell PLC. https://reports.shell.com/annual-report/2020/strategic-report/segments/oil-products/data-tables.php.

Shell. 2021d. *Shell Sustainability Report 2020*. The Hague: Royal Dutch Shell PLC. https://reports.shell.com/sustainability-report/2020.

Shires, Theresa M., Christopher J. Loughran, Stephanie Jones, and Emily Hopkins. 2009. *Compendium of Greenhouse Gas Emissions Methodologies for the Oil and Natural Gas Industry*. Washington DC: API. https://www.api.org/~/media/files/ehs/climate-change/2009_ghg_compendium.ashx.

Statista. 2021. “Statista Dossier on the Six Largest Public Oil and Gas Supermajors.” https://www.statista.com/study/61288/oil-supermajors.

Sun, Pingping, Ben Young, Amgad Elgowainy, Zifeng Lu, Michael Wang, Ben Morelli, and Troy Hawkins. 2019. “Criteria Air Pollutant and Greenhouse Gases Emissions from US Refineries Allocated to Refinery Products.” *Environmental Science and Technology* 53, no. 11 (2019): 6556–6569. https://doi.org/10.1021/acs.est.8b05870.

TotalEnergies. 2007. *TotalEnergies Factbook 2006*. Courbevoie: TotalEnergies SE. https://totalenergies.com/sites/g/files/nytnzq121/files/atoms/files/factbook_2006.pdf.

TotalEnergies. 2010. *TotalEnergies Factbook 2009*. Courbevoie: TotalEnergies SE. https://totalenergies.com/sites/g/files/nytnzq121/files/atoms/files/factbook_2009.pdf.

TotalEnergies. 2015. *TotalEnergies Factbook 2014*. Courbevoie: TotalEnergies SE. https://totalenergies.com/sites/g/files/nytnzq121/files/atoms/files/factbook_2014_v2_0.pdf.

TotalEnergies. 2020a. *Getting to Net Zero*. Courbevoie: TotalEnergies SE. https://www.total.com/sites/g/files/nytnzq111/files/documents/2020-10/total-climate-report-2020.pdf.

TotalEnergies. 2020b. *TotalEnergies Factbook 2019*. Courbevoie: TotalEnergies SE. https://www.total.com/sites/g/files/nytnzq111/files/documents/2020-07/Factbook_2019.pdf.

TotalEnergies. 2021. *Universal Registration Document 2020*. Courbevoie: TotalEnergies SE, March 2021. https://totalenergies.com/system/files/documents/2021-03/2020-universal-registration-document.pdf#page=219.

U.S. Energy Information Administration. 2017. “The API Gravity of Crude Oil Produced in the U.S. Varies Widely Across States.” April 19, 2017. https://www.eia.gov/todayinenergy/detail.php?id=30852.

U.S. Energy Information Administration. 2018. “About 7% of Fossil Fuels are Consumed for Non-Combustion Use in the United States.” April 6, 2018. https://www.eia.gov/todayinenergy/detail.php?id=35672.

U.S. Energy Information Administration. 2020a. “Monthly Energy Reviews.” https://www.eia.gov/totalenergy/data/monthly/previous.php.

U.S. Energy Information Administration. 2020b. “Oil and Petroleum Products Explained.” September 23, 2020. https://www.eia.gov/energyexplained/oil-and-petroleum-products/refining-crude-oil-the-refining-process.php.

U.S. Energy Information Administration. 2021a. “Global Petroleum Liquids Consumption: Short-Term Energy Outlook.” July 7, 2021. https://www.eia.gov/outlooks/steo/report/global_oil.php.

U.S. Energy Information Administration. 2021b. “Oil and Petroleum Products Explained.” February 11, 2021. https://www.eia.gov/energyexplained/oil-and-petroleum-products/prices-and-outlook.php.

U.S. Environmental Protection Agency (U.S. EPA). 1995. “AP-42: Compilation of Air Emissions Factors.” https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors.

U.S. Environmental Protection Agency (U.S. EPA). 2009. *Technical Support Document for the Petroleum Refining Sector: Proposed Rule for Mandatory Reporting of Greenhouse Gases*. Washington DC: EPA. https://www.epa.gov/sites/default/files/2015-06/documents/ghg-mrr-finalpreamble.pdf.

U.S. Environmental Protection Agency (U.S. EPA). 2017. “Regulations for Greenhouse Gas Emissions from Commercial Trucks & Buses,” November 2017. https://www.epa.gov/regulations-emissions-vehicles-and-engines/regulations-greenhouse-gas-emissions-commercial-trucks.

U.S. Environmental Protection Agency (U.S. EPA). 2021. “Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2019.” https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019.

UN News. 2016. “‘Today is an Historic Day,’ says Ban, as 175 Countries Sign Paris Climate Accord,” UN News, April 22, 2016. https://news.un.org/en/story/2016/04/527442-today-historic-day-says-ban-175-countries-sign-paris-climate-accord#.VxqAYGNpr-Y.

Wang, Jingfan, John O’Donnell, and Adam R. Brandt. 2016. “Potential Solar Energy Use in the Global Ppetroleum Sector.” *Energy* 30 (2016): 1–9. https://www.sciencedirect.com/science/article/pii/S0360544216315535.

Wang, Michael Q. 1999. “GREET 1.5: Transportation Fuel-Cycle Model. Vol. 1: Methodology, Development, Use, and Results.” No. ANL/ESD-39-VOL-1, Argonne: Argonne National Laboratory. https://doi.org/10.2172/14775.

Wang, Michael. 2008. “The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model: Version 1.5.” Center for Transportation Research, Argonne National Laboratory. http://eng.sut.ac.th/transportenergy/data/paper4web/The%20GHG%20regulated%20emission%20and%20energy%20use%20in%20transportation%20model%20-%2099.pdf.

Wiedmann, Thomas and Jan Minx. 2008. “A Definition of ‘Carbon Footprint’.” *Ecological Economics Research Trends* 1 (2008): 1–11. https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.467.6821&rep=rep1&type=pdf.

Wood Mackenzie. 2015. “Oil Refining & Marketing Analysis.” https://www.woodmac.com/our-expertise/capabilities/oil-refining-marketing.

World Bank. 2021. *Global Gas Flaring Tracker Report*. Washington DC: The World Bank Group. https://www.worldbank.org/en/topic/extractiveindustries/publication/global-gas-flaring-tracker-report.

APPENDICES

APPENDIX 1 DATA SUMMARY OF OCI DATASET

SAMPLE SIZE		71			
	UNIT	AVERAGE	MINIMUM	MAXIMUM	TRANSPORT
Field depth	ft	7,924.81	65.00	36,000.00	5,202.60
offshore^		0.44	0.00	1.00	0.50
Field production rate	bbl/d	314,382.04	266.00	5,000,000.00	63,7741.71
API		32.70	8.60	66.64	10.01
# of producer & injector wells		2,155.68	2.00	34679.00	5,718.75
Crude ecosystem carbon richness^		1.37	0.00	3.00	0.72
Field development intensity^		1.73	0.00	3.00	0.81
Diameter	in	3.56	2.75	9.63	1.41
Productivity index	bbl/psi-d	159.03	3.00	10,000.00	1,185.36
Average reservoir pressure	psi	2,685.57	13.98	15,000.00	2,280.87
Gas-oil ratio (GOR)	scf/bbl oil	3,029.52	29.65	30,503.00	5,518.43
Water oil ratio (WOR)	bbl water/bbl oil	5.61	0.05	37.40	9.44
Water injection ratio	bbl water/bbl oil	5.74	0.00	39.98	8.90
Steam oil ratio (SOR)	bbl steam/bbl oil	2.62	0.00	5.79	1.13
Fraction of remaining gas to reinjection		0.09	0.00	1.00	0.25
Fraction of water to reinjection/flooding		0.91	0.00	1.00	0.26
Fraction of electricity generated from cogen		0.15	0.00	1.00	0.36
Heater/treater^		0.16	0.00	1.00	0.37
Stabilizer column^		0.68	0.00	1.00	0.47
N_2 (gas position %)	%	1.88	0.10	3.67	0.62
CO_2 (gas position %)	%	5.02	0.24	6.10	1.84
C1 (gas position %)	%	82.47	49.24	97.49	8.88
C2 (gas position %)	%	5.16	0.52	21.03	4.28
C3 (gas position %)	%	2.74	0.24	15.09	3.00
C4+ (gas position %)	%	1.74	0.12	12.20	2.36
H_2S (gas position %)	%	0.99	0.00	15.00	1.73
Ocean tanker (transport mode)	Mile	6,175.59	0.00	13,605.06	4726.01
Barge (transport mode)	Mile	5.65	0.00	133.60	27.07
Pipeline (transport mode)	Mile	313.39	0.00	3,288.00	482.26
Rail (transport mode)	Mile	31.13	0.00	999.99	166.73
Sulfur	% wt	1.05	0.00	8.13	1.32
Drilling	kg CO_2e/bblCrude	6.20	0.23	41.72	8.21
Production	kg CO_2e/bblCrude	14.89	0.00	190.01	33.15
Processing	kg CO_2e/bblCrude	7.59	0.04	72.54	12.10
transport to Refinery	kg CO_2e/bblCrude	5.13	0.07	15.39	3.12
Net lifecycle emissions	kg CO_2e/bblCrude	65.43	21.02	179.76	39.36
Electricity	kg CO_2e/bblCrude	2.13	0.73	5.30	1.06
Heat	kg CO_2e/bblCrude	15.62	7.61	26.97	4.48
Steam	kg CO_2e/bblCrude	2.66	1.35	6.50	1.28
Hydrogen via SMR	kg CO_2e/bblCrude	9.50	-0.34	53.45	13.57
Fluid catalytic cracking regeneration	kg CO_2e/bblCrude	2.00	0.00	6.49	1.97
Total refinery processes	kg CO_2e/bblCrude	31.93	9.70	98.70	21.39

The following Appendices are available at: https://ccsi.columbia.edu/content/oil-supermajors-carbon-footprint-refining-sales-climate-change

APPENDIX 2 TIME-SERIES COUNTRY-SPECIFIC UPSTREAM EMISSION FACTORS (Kg CO_2e/Bbl)

Note: Destination countries/regions represent the locations where crude oil products are refined. Thus, the data takes accounts to import/export of crude oil products. API is weighted-average by volume. We apply the time series change generated by Decision-Tree Model to the country-specific upstream emission factors of the 83 destination countries (oil consuming countries) in 2015 (Jing, et al. 2020) to calculate the time-series country-specific upstream emission factors.

APPENDIX 4 TIME-SERIES COUNTRY-SPECIFIC MIDSTREAM EMISSION FACTORS (Kg CO_2e/Bbl)

Note: Destination countries/regions represent the locations where crude oil products are refined. Thus, the data takes accounts to import/export of crude oil products. API is weighted-average by volume. We apply the time series change generated by Decision-Tree Model to the country-specific midstream emission factors of the 83 destination countries (oil consuming countries) in 2015 (Jing, et al. 2020) to calculate the time-series country-specific midstream emission factors.

APPENDIX 5 TIME-SERIES COUNTRY-SPECIFIC DOWNSTREAM EMISSION FACTORS (Kg CO_2e/Bbl)

Note: Destination countries/regions represent the locations where refined products are sold. Thus, the data takes into accounts the import/export of refined products when calculating transportation from the refining sector to the petroleum products sales sector. We apply the time series change generated by Decision-Tree Model to the country-specific downstream emission factors of the 83 destination countries (oil consuming countries) in 2015 (Jing, et al. 2020) to calculate the time-series country-specific downstream emission factors.

APPENDIX 6 TIME-SERIES COUNTRY-SPECIFIC LIFE-CYCLE OIL GHG EMISSION FACTORS (Kg CO_2e/Bbl)

APPENDIX 3 TIME SERIES DEFAULT EMISSION FACTORS USED IN OPGEE MODEL

G/MMBTU OF FUEL BURNED-LOWER HEATING VALUE		1990	1995	2000	2005	2010	2015	2020
Natural gas	Utility/ Industrial Boiler (>100 MMBtu/hr input)	59,766.09	59,766.09	59,766.09	59,765.74	59,660.36	59,660.36	59,660.36
	Small Industrial Boiler (10-100 MMBtu/hr input)	59,766.09	59,766.09	59,766.09	59,765.91	59,541.24	59,541.24	59,541.24
	Large Gas Turbine	59,955.28	59,955.28	59,955.28	59,955.21	59,467.74	59,467.74	59,467.74
	CC Gas Turbine	59,955.21	59,955.21	59,955.21	59,955.15	59,473.96	59,473.96	59,473.96
	Small Turbine	59,955.28	59,955.28	59,955.28	59,955.21	59,467.74	59,467.74	59,467.74
	Stationary Reciprocating Engine	68,096.48	68,096.48	68,096.48	68,087.09	68,193.59	68,193.59	68,111.36
Diesel fuel	Industrial Boiler	78,319.76	78,319.76	78,319.76	78,319.75	78,477.61	78,477.61	78,314.28
	Commercial Boiler	78,332.67	78,332.67	78,332.67	78,332.65	78,490.29	78,490.29	78,490.29
	Stationary Reciprocating Engine	78,902.11	78,902.11	79,240.22	78,894.21	78,490.51	78,490.51	78,281.21
	Turbine	78,814.06	78,814.06	78,814.06	78,814.06	78,446.07	78,446.07	78,446.07
Crude	Industrial Boiler	77,909.92	77,909.92	77,909.92	77,909.92	75,442.63	75,442.63	75,442.63
Residual oil	Industrial Boiler	85,261.05	85,261.05	85,261.05	85,261.04	85,664.31	85,664.31	85,664.31
Pet. coke	Industrial Boiler	107,365.71	107,365.71	107,365.71	107,363.69	107,259.80	107,259.80	107,259.80
Coal	Industrial Boiler	100,433.84	100,433.84	100,433.84	100,431.82	100,327.93	100,327.93	100,327.93
Upgrader process gas	Stationary reciprocating engine	68,096.48	68,096.48	68,096.48	68,087.09	68,193.59	68,193.59	68,111.36
NGL	Diluent combustion	66,422.13	66,422.13	664,22.13	664,22.13	66,422.13	66,422.13	66,422.13

Note: Default emission factors used in OPGEE Model are the combustion emission factors for different fuels combusted in different engines in crude oil production process.

Source: GREET Model (Cai, Sykora and Wang, Building Life-Cycle Analysis with the GREET Building Module: A User Guide 2021).

APPENDIX 7 UPSTREAM EMISSIONS KEY VARIABLES BY CATEGORIES

FIELD PROSPERITIES	PRODUCTION PRACTICE	PROCESSING PRACTICE	OTHERS
• Field location. • Field is onshore/offshore. • Field depth. • API gravity. • Diameter of wells. • Productivity index. • Field production rate. • Amount of producing wells. • Amount of water injecting wells. • Average reservoir pressure.	• Gas position. • Gas-oil ratio. • Water-oil ratio. • Water-injection ratio. • Steam-oil ratio. • Fraction of required electricity generated on site. • Fraction of remaining gas reinjected. • Fraction of water produced reinjected.	• Use of heater/treaters and stabilizer columns during oil phase separation.	• Land use impact: Parameters that determine the GHG emissions from land use change, including ecosystem carbon richness and field development intensity. • Crude oil transport: Transport mode, distance, ocean tanker size.

Source: OPGEE Model (El-Houjeiri and Brandt. 2017).

Below are definitions of these variables (El-Houjeiri and Brandt. 2017):

- Offshore: dummy variable[36] indicating whether the oilfield is onshore or offshore.
- Crude ecosystem carbon richness: cluster variables[37] measuring the total carbon density of all components in the ecosystem within the area; carbon intensity can be low, moderate, or high.
- Field depth: determines the reservoir pressure and the injection downhole pressure, thus affecting the productivity of the oil field. It is also a widely-ranged variable. According to a dataset of 4489 field depth data points collected from the Oil & Gas Journal's 2010 Worldwide Oil Field Production Survey, the mean depth is 7240 ft and the standard deviation is 3,591 ft (Oil & Gas Journal 2010).
- API gravity: measurement benchmark for crude oil grade (heavy, medium, and light); it determines several key parameters, such as gas-to-oil ratio, defined below, and production facilities, such as upgrading configurations.[38]
- Ecosystem carbon richness: cluster variable, categorized by low, moderate, and high, and measuring GHG emissions per unit of developed land.
- Field development intensity: also a cluster variable categorized by low, moderate, and high, and measuring the significance level of land disturbances. Ecosystem carbon richness and field development intensity determine the GHG emissions from land-use change (El-Houjeiri and Brandt. 2017).
- Gas-to-oil ratio (GOR): measures the units of gas stream per unit of oil (scf/bbl), which reveals non-petroleum emission sources during the oil production process.
- Water-to-oil ratio (WOR): measures the amount of water used in oil production per unit of oil.
- Water injection ratio: affects the energy consumed in injecting water into the reservoir (water flooding).
- Steam oil ratio: affects the energy consumed in producing thermal oil.
- Heater/treater: dummy variable indicating whether a heater/treater is used in the oil producing process. A heater/treater is a machine that uses heat to facilitate oil-water separation.
- Stabilizer: dummy variable indicating whether a stabilizer is used in the oil producing process to reduce crude oil temperature.

FOOTNOTES

[36] Dummy variable is valued at 0 or 1 to indicate respectively the absence or presence of a categorical effect that may affect the outcome.

[37] Cluster variable Indicates different categories of the data.

[38] Facilities to upgrade heavy oil into more valuable petroleum products.

APPENDIX 8 UNIVARIATE REGRESSION OF EMISSIONS IN DIFFERENT STAGES ON KEY INPUTS IN OPGEE MODEL

TRANSPORT	TRANSPORT	EMISSION	EMISSION	DISTANCE)	TRANSPORT
Field depth	-0.0003 (0.0002)	-0.0015 (0.0010)	0.0002 (0.0002)	-0.0001 (0.0001)	-0.0011 (0.0008)
offshore^	-6.6185 (1.6086) *	-14.9316 (6.7993)	0.4479 (2.7719)	0.1667 (0.7077)	-19.8123 (8.5705) *
Field production rate	-0.0000 (0.0000)	-0.0000 (0.0000)	-0.0000 (0.0000)	0.0000 (0.0000) *	-0.0000 (0.0000)
API	-0.2324 (0.1397) *	-0.8100 (0.4563) *	0.4497 (0.2528) *	0.0099 (0.0373)	-0.2958 (0.6411)
# of producer & injector wells	0.0001 (0.0001)	0.0010 (0.0008)	-0.0003 (0.0001)	-0.0001 (0.0001)	0.0001 (0.0006)
Crude ecosystem carbon richness^	7.5162 (1.8234) *	2.0158 (8.2430)	2.5272 (2.9891)	-0.0900 (0.4770)	14.7015 (7.6752) *
Field development intensity^	4.4552 (1.6055) *	10.8831 (6.8127) *	0.7232 (2.0042)	0.0448 (0.4153)	14.9944 (6.2095) *
Diameter	0.1594 (0.7360)	-0.4890 (1.7969)	-0.9511 (0.5913)	0.0321 (0.3008)	-3.3305 (2.5010)
Productivity index	0.0001 (0.0001)	-0.0014 (0.0004)	-0.0003 (0.0002)	0.0002 (0.0000)	0.0003 (0.0006)
Average reservoir pressure	-0.0004 (0.0003)	-0.0030 (0.0018)	0.0007 (0.0007)	-0.0002 (0.0002)	-0.0027 (0.0013)
Gas-oil ratio (GOR)	0.0000 (0.0001)	-0.0001 (0.0006)	0.0020 (0.0004) *	-0.0000 (0.0000)	0.0025 (0.0008) *
Water oil ratio (WOR)	0.1238 (0.0975)	1.0241 (0.3376) *	-0.0728 (0.0762)	-0.0863 (0.0290) *	0.6318 (0.3757)
Water injection ratio	0.0888 (0.0953)	0.9573 (0.3554) *	-0.0455 (0.0845)	-0.0819 (0.0330) *	0.5734 (0.4180)
Steam oil ratio (SOR)	-0.9441 (0.9392)	10.0274 (5.6078) *	0.3261 (0.7080)	0.5187 (0.3315)	7.3842 (5.3862)
Fraction of remaining gas to reinjection	-4.8502 (1.8464)	-0.1073 (10.4997)	0.6334 (3.0906)	-0.7373 (1.2413)	-9.6534 (14.0238)
Fraction of water to reinjection/flooding	-1.4480 (2.3504)	-15.4092 (23.5583)	3.2254 (3.0107)	2.6413 (1.3031)	-18.3397 (27.9839)
Fraction of electricity generated from cogen	-3.8017 (1.3524)	-3.6855 (6.5580)	1.8033 (2.2945)	-0.3926 (0.7908)	-13.3460 (8.5824)
Heater/treater^	3.9934 (3.5910)	1.4953 (8.8756)	-1.1521 (2.5065)	-1.2701 (0.9431)	18.2017 (15.2577)
Stabilizer column^	-3.4720 (2.5867)	-20.7582 (11.2298) *	8.6984 (2.0374) *	0.2764 (0.9263)	-2.9912 (11.0418)
N_2 (gas position)	-4.0188 (2.2212) *	1.6370 (2.7672)	-0.8353 (1.0593)	0.8887 (0.3164)	-10.2075 (9.9801)
CO_2 (gas position)	0.1042 (0.4140)	2.1962 (1.2907)	0.4593 (0.4287)	0.1737 (0.1603)	2.1699 (2.3228)
C1 (gas position)	-0.0256 (0.0985)	0.3496 (0.1242)	-0.0056 (0.0732)	0.0030 (0.0326)	0.4832 (0.5128)
C2 (gas position)	0.0481 (0.1834)	-0.8609 (0.2945)	0.0208 (0.1732)	-0.0519 (0.0613)	-0.7469 (1.2496)
C3 (gas position)	0.2184 (0.2932)	-1.0732 (0.3965)	-0.0157 (0.2310)	-0.1068 (0.0709)	-1.2639 (1.5562)
C4+ (gas position)	0.3328 (0.3478)	-1.5951 (0.6264)	-0.0102 (0.3241)	-0.0839 (0.1057)	-1.7666 (1.9047)
H_2S (gas position)	-0.4955 (0.2511)	-0.4491 (0.5944)	-0.3288 (0.1173)	0.4045 (0.0495)	-2.2180 (0.8214)
Ocean tanker (transport mode)	-0.0002 (0.0002)	-0.0006 (0.0011)	0.0001 (0.0001)	0.0006 (0.0000) *	-0.0005 (0.0010)
Barge (transport mode)	0.0110 (0.0076)	-0.1078 (0.0304)	0.0096 (0.0196)	-0.0236 (0.0028)	0.1123 (0.2656)
Pipeline (transport mode)	0.0024 (0.0017)	0.0003 (0.0032)	-0.0024 (0.0016)	0.0017 (0.0011) *	-0.0088 (0.0060)
Rail (transport mode)	-0.0020 (0.0011)	-0.0147 (0.0045)	-0.0049 (0.0016)	-0.0000 (0.0005)	-0.0095 (0.0220)

Note: This table reports coefficients from univariate regression of drilling, production, processing, transport to refinery, and total upstream emission on key inputs in the OPGEE Model. Standard errors are reported in parentheses. ^ after coefficients denotes significance at the 5% level. * after parameter names denotes dummy variables.

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> “The six supermajors—BP, Chevron, Eni, ExxonMobil, Shell, and TotalEnergies—own a sizable share of the oil refining and petroleum products sales sectors. Focusing only on their extractive activities conceals the depth of their hold on oil value chains. This report sheds light on their contribution to greenhouse gas emissions from the midstream and downstream levels of the value chain.”

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