Plastic & Climate

THE HIDDEN COSTS OF A PLASTIC PLANET

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#break free from plastic

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Center for International Environmental Law (CIEL) uses the power of law to protect the environment, promote human rights, and ensure a just and sustainable society. CIEL seeks a world where the law reflects the interconnection between humans and the environment, respects the limits of the planet, protects the dignity and equality of each person, and encourages all of earth's inhabitants to live in balance with each other.

Environmental Integrity Project (EIP) is a nonprofit, nonpartisan organization that empowers communities and protects public health and the environment by investigating polluters, holding them accountable under the law, and strengthening public policy.

FracTracker Alliance is a nonprofit organization that studies, maps, and communicates the risks of oil and gas development to protect our planet and support the renewable energy transformation.

Global Alliance for Incinerator Alternatives (GAIA) is a worldwide alliance of more than 800 grassroots groups, non-governmental organizations, and individuals in over 90 countries whose ultimate vision is a just, toxic-free world without incineration.

5Gyres is a nonprofit organization focused on stopping the flow of plastic pollution through science, education, and adventure. We employ a science to solutions model to empower community action, engaging our global network in leveraging science to stop plastic pollution at the source.

#breakfreefromplastic is a global movement envisioning a future free from plastic pollution made up of 1,400 organizations from across the world demanding massive reductions in single-use plastic and pushing for lasting solutions to the plastic pollution crisis.

Contents

Figures, Tables, Boxes

Acronyms

AR4	IPCC's Fourth Assessment Report (See IPCC AR4)
AR5	IPCC's Fifth Assessment Report (See IPCC AR5)
°C	Degrees Celsius
CCUS	Carbon capture, usage, and storage
C_2H_4	Ethylene
CH_4	Methane
CIEL	Center for International Environmental Law
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DHS	Department of Homeland Security
EIA	Energy Information Administration
EPR	Extended producer responsibility
EPS	Expanded polystyrene
EU	European Union
FERC	Federal Energy Regulatory Commission
GHG	Greenhouse gas
Gt	Gigaton
GWP_{100}	Global warming potential over 100 years
HDPE	High-density polyethylene
HFCs	Hydrofluorocarbons
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Chance
IPCC AR4	IPCC's Fourth Assessment Report (See AR4)
IPCC AR5	IPCC's Fifth Assessment Report (See AR5)
IPCC SAR	IPCC's Second Assessment Report (See SAR)
IPCC SR 1.5	IPCC's Special Report on Global Warming of 1.5°C (See SR 1.5)
Kg	Kilogram
kWh	Kilowatt hours
LNG	Liquefied natural gas
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
MRF	Material recovery facility
MMcf	Million cubic feet
Mt	Metric ton
MSW	Municipal solid waste
MW	Megawatt
N_2O	Nitrous oxide
NEI	National Emissions Inventory
NGLs	Natural gas liquids
OGTM	Oil & Gas Threat Map
PE	Polypropylene
PET	Polyethylene terephthalate
PFCs	Perfluorocarbons
PHA	Polyhydroxyalkanoate
PHMSA	Pipeline and Hazardous Materials Safety Administration
PLA	Polylactic acid
PP	Polypropylene
PP&A	Polyester, polyamide, and acrylic fibers
PS	Polystyrene
PTF	Plastic-to-fuel
PUR	Polyurethane
PVC	Polyvinyl chloride
RECs	Reduced emissions technologies
SAR	IPCC's Second Assessment Report (See IPCC SAR)
SF_6	Sulfur hexafluoride
SR 1.5	IPCC's Special Report on Global Warming of 1.5°C (See IPCC SR 1.5)
Syngas	Synthetic natural gas
US	United States
USEPA	US Environmental Protection Agency
WTE	Waste-to-energy
WEF	World Economic Forum

Glossary of Terms

Anaerobic digestion
Process of converting organic waste to biogas in the absence of oxygen.

Biodegradable
Capable of breaking down into its chemical constituents in the natural environment.

Business as usual
The baseline or reference case scenario that represents the current rates of emissions against which market, technological, and policy initiatives to reduce emissions are measured.

Carbon budget
The total amount of carbon emissions that can be emitted for temperatures to remain at or below a specified limit.

Carbon dioxide equivalent
A measure used to compare the emissions from various greenhouse gases based upon their global warming potential.

Circular systems
Intentionally designed industrial systems in which output from one system becomes input for that system or another industrial system, thereby minimizing the creation and disposal of waste and minimizing the need for raw material extraction.

Climate forcing
Climate forcing is the dynamic whereby the varying amounts of external influences, including surface reflectivity, atmospheric aerosols, and human-induced changes in greenhouse gases alter the balance of energy entering and leaving the Earth system.

Expanded polystyrene
A lightweight foam formed from polystyrene that is commonly misidentified as the brand name Styrofoam. It is used for items such as cups, food trays, and cushioning material.

Fracking
Hydraulic fracturing, a pressurized process in which underground rock formations (shale) are cracked, or fracked, to release trapped oil and gas.

Gasification
The thermal decomposition and partial oxidation of waste materials at temperatures generally above 400°C using a limited amount of air or oxygen, resulting in solid residues and a gaseous mixture.

Gigaton
Equal to one billion metric tons.

Hauler
Waste transporter operating truck(s) that haul waste from point of collection to material recovery facility (MRF), from MRF to dump site, or both. Services are typically contracted by local governments but often managed directly by public authorities.

Incineration
Thermal decomposition and rapid oxidation of waste material at temperatures generally above 230°C with the addition of air or oxygen at sub-stoichiometric to excess levels, resulting in solid residues and a gaseous mixture.

Intergovernmental Panel on Climate Change
Established in 1988 by the World Meteorological Organization and United Nations Environment Programme, the Intergovernmental Panel on Climate Change is the international body that provides policy makers with regular assessments of the scientific basis of climate change, its impacts and risks, and options for adaptation and mitigation.

Landfilling
Disposal of waste in a waste pile that is usually underground and may be sanitary (i.e., measures have been taken to prevent leachate) or unsanitary (no prevention measures have been taken).

Low-value plastic
Plastic waste materials that do not have value in local recycling markets (e.g., grocery bags, thin films, composite plastics, and residual polypropylene). Polystyrene, polyvinyl chloride, and polypropylene are considered “medium value,” with approximately 25 percent being recycled locally.

Mandatory recycled content
Minimum requirement for use of recycled content in products.

Material design
Redesign of products to meet specifications intended to make the products either more attractive for material- or energy-extraction markets or less likely to leak into the ocean.

Material recovery facility
Facility used for separating different materials from the waste stream.

Mixed waste
Unseparated or unsorted waste.

Municipal solid waste
Waste generated by households and sometimes including streams of commercial and industrial waste.

Negative emissions
The end result of processes that remove carbon dioxide from the atmosphere.

Off-gassing
The release of gases into the air as a byproduct of a chemical process.

Petrochemicals
Fossil-fuel-derived chemicals, some of which are used to produce plastic.

Plastic waste leakage
Movement of plastic from land-based sources into the ocean.

Polymer
Chemical combination of smaller particles.

Pyrolysis
The thermal decomposition of waste materials at temperatures beginning around 200°C without the addition of air or oxygen, resulting in solid and/or liquid residues as well as a gaseous mixture.

Thin film
Mixed plastic film, typically constructed of some variation of polyethylene.

Waste
Any discarded material, such as household or municipal garbage, trash or refuse, food wastes, or yard wastes, that no longer has value in its present form but may or may not be recyclable or otherwise able to be repurposed.

Waste-to-energy
The process of treating waste through incineration or other thermal processing with a purpose of generating energy (electricity or heat).

Zero waste
The conservation of all resources by means of responsible production, consumption, reuse, and recovery of materials without incineration or landfilling.

EXECUTIVE SUMMARY

Plastic Proliferation Threatens the Climate on a Global Scale

The plastic pollution crisis that overwhelms our oceans is also a significant and growing threat to the Earth's climate. At current levels, greenhouse gas emissions from the plastic lifecycle threaten the ability of the global community to keep global temperature rise below 1.5°C. With the petrochemical and plastic industries planning a massive expansion in production, the problem is on track to get much worse.

If plastic production and use grow as currently planned, by 2030, these emissions could reach 1.34 gigatons per year—equivalent to the emissions released by more than 295 new 500-megawatt coal-fired power plants. By 2050, the cumulation of these greenhouse gas emissions from plastic could reach over 56 gigatons—10–13 percent of the entire r emaining carbon budget.

Nearly every piece of plastic begins as a fossil fuel, and greenhouse gases are emitted at each of each stage of the plastic lifecycle: 1) fossil fuel extraction and transport, 2) plastic refining and manufacture, 3) managing plastic waste, and 4) its ongoing impact in our oceans, waterways, and landscape.

This report examines each of these stages of the plastic lifecycle to identify the major sources of greenhouse gas emissions, sources of uncounted emissions, and uncertainties that likely lead to underestimation of plastic's climate impacts. The report compares greenhouse gas emissions estimates against global carbon budgets and emissions commitments, and it considers how current trends and projections will impact our ability to reach agreed emissions targets. This report compiles data, such as downstream emissions and future growth rates, that have not previously been accounted for in widely used climate models. This accounting paints a grim picture: plastic proliferation threatens our planet and the climate at a global scale.

> At current levels, greenhouse gas emissions from the plastic lifecycle threaten the ability of the global community to keep global temperature rise below 1.5°C degrees. By 2050, the greenhouse gas emissions from plastic could reach over 56 gigatons—10-13 percent of the entire remaining carbon budget.

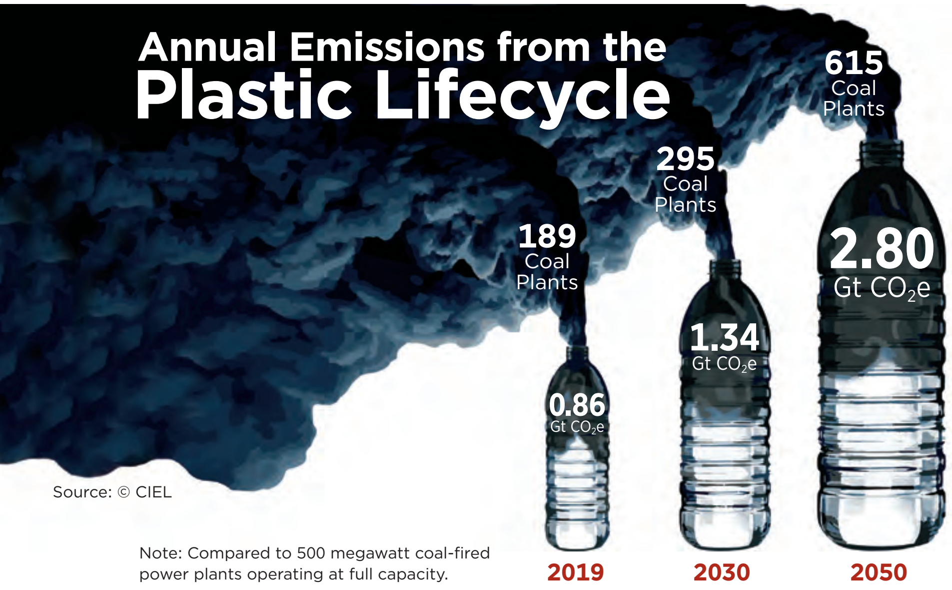
Due to limitations in the availability and accuracy of certain data, estimates in this report should be considered conservative; the greenhouse gas emissions from the plastic lifecycle are almost certainly higher than those calculated here. Despite these uncertainties, the data reveal that the climate impacts of plastic are real, significant, and require urgent attention and action to maintain a survivable climate.

The report includes recommendations for policymakers, governments, nonprofits, funders, and other stakeholders to help stop the expanding carbon emissions of plastic production. The most effective recommendation is simple: immediately reduce the production and use of plastic. Stopping the expansion of petrochemical and plastic production and keeping fossil fuels in the ground is a critical element to address the climate crisis.

Opposite: © Carroll Muffett/CIEL

FIGURE 1

Emissions from the Plastic Lifecycle



Source: © CIEL

Note: Compared to 500 megawatt coal-fired power plants operating at full capacity.

KEY FINDINGS

Current Greenhouse Gas Emissions from the Plastic Lifecycle Threaten Our Ability to Meet Global Climate Targets

In 2019, the production and incineration of plastic will add more than 850 million metric tons of greenhouse gases to the atmosphere—equal to the emissions from 189 five-hundred-megawatt coal power plants. At present rates, these greenhouse gas emissions from the plastic lifecycle threaten the ability of the global community to meet carbon emissions targets.

- **Extraction and Transport**
  The extraction and transport of fossil fuels for plastic production produces significant greenhouse gases. Sources include direct emissions, like methane leakage and flaring, emissions from fuel combustion and energy consumption in the process of drilling for oil or gas, and emissions caused by land disturbance when forests and fields are cleared for wellpads and pipelines.

  In the United States alone in 2015, emissions from fossil fuel (largely fracked gas) extraction and production attributed to plastic production were at least 9.5–10.5 million metric tons of CO_2 equivalents (CO_2e) per year. Outside the US, where oil is the primary feedstock for plastic production, approximately 108 million metric tons of CO_2e per year are attributable to plastic production, mainly from extraction and refining.

- **Refining and Manufacture**
  Plastic refining is among the most greenhouse-gas-intensive industries in the manufacturing sector—and the fastest growing. The manufacture of plastic is both energy intense and emissions intensive in its own right, producing significant emissions through the cracking of alkanes into olefins, the polymerization and plasticization of olefins into plastic resins, and other chemical refining processes. In 2015, 24 ethylene facilities in the US produced 17.5 million metric tons of CO_2e, emitting as much CO_2 as 3.8 million passenger vehicles. Globally in 2015, emissions from cracking to produce ethylene were 184.3–213.0 million metric tons of CO_2e, as much as 45 million passenger vehicles driven for one year. These emissions are rising rapidly: a new Shell ethane cracker being constructed in Pennsylvania could emit up to 2.25 million tons of CO_2e each year; a new ethylene plant at ExxonMobil's Baytown, Texas, refinery could release up to 1.4 million tons. Annual emissions from just these two new facilities would be equal to adding almost 800,000 new cars to the road. Yet they are only two among more than 300 new petrochemical projects being built in the US alone—primarily for the production of plastic and plastic feedstocks. As this report documents, moreover, these figures do not capture the wide array of other emissions from plastic production processes.

- **Waste Management**
  Plastic is primarily landfilled, recycled, or incinerated—each of which produces varying amounts of greenhouse gas emissions. Landfilling emits the least greenhouse gases on an absolute level, although it presents significant other risks. Recycling has a moderate emissions profile but displaces new virgin plastic on the market, making it advantageous from an emissions perspective. Incineration leads to extremely high emissions and is the primary driver of emissions from plastic waste management. Globally, the use of incineration in plastic waste management is poised to grow dramatically in the coming decades.

  US emissions from plastic incineration in 2015 are estimated at 5.9 million metric tons of CO_2e. For plastic packaging, which represents

40 percent of plastic demand, global emissions from incineration of this particular type of plastic waste totaled 16 million metric tons of CO_2e in 2015. This estimate does not account for 32 percent of plastic packaging waste that is known to remain unmanaged, open burning of plastic or incineration that occurs without any energy recovery, or practices that are widespread and difficult to quantify.

- **Plastic in the Environment**
  Plastic that is unmanaged ends up in the environment, where it continues to have climate impacts as it degrades. Efforts to quantify those emissions are still in the early stages, but a first-of-its-kind study from Sarah-Jeanne Royer and her team demonstrates that plastic at the ocean's surface continually releases methane and other greenhouse gases, and that these emissions increase as the plastic breaks down further. Current estimates address only the one percent of plastic at the ocean's surface. Emissions from the 99 percent of plastic that lies below the ocean's surface cannot yet be estimated with precision. Significantly, Royer's research showed that plastic on the coastlines, riverbanks, and landscapes releases greenhouse gases at an even higher rate.

  Microplastic in the oceans may also interfere with the ocean's capacity to absorb and sequester carbon dioxide. Earth's oceans have absorbed 20-40 percent of all anthropogenic carbon emitted since the dawn of the industrial era. Microscopic plants (phytoplankton) and animals (zooplankton) play a critical role in the biological carbon pump that captures carbon at the ocean's surface and transports

In 2019, the production and incineration of plastic will produce more than 850 million metric tons of greenhouse gases—equal to the emissions from 189 five-hundred-megawatt coal power plants.

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it into the deep oceans, preventing it from reentering the atmosphere. Around the world, these plankton are being contaminated with microplastic. Laboratory experiments suggest this plastic pollution can reduce the ability of phytoplankton to fix carbon through photosynthesis. They also suggest that plastic pollution can reduce the metabolic rates, reproductive success, and survival of zooplankton that transfer the carbon to the deep ocean. Research into these impacts is still in its infancy, but early indications that plastic pollution may interfere with the largest natural carbon sink on the planet should be cause for immediate attention and serious concern.

Plastic Production Expansion and Emissions Growth Will Exacerbate the Climate Crisis

The plastic and petrochemical industries' plans to expand plastic production threaten to exacerbate plastic's climate impacts and could make limiting global temperature rise to 1.5°C impossible. If the production, disposal, and incineration of plastic continue on their present growth trajectory, by 2030, these global emissions could reach 1.34 gigatons per year—equivalent to more than 295 five-hundred-megawatt coal plants. By 2050, plastic production and incineration could emit 2.8 gigatons of CO_2 per year, releasing as much emissions as 615 five-hundred-megawatt coal plants.

Critically, these annual emissions will accumulate in the atmosphere over time. To avoid overshooting the 1.5°C target, aggregate global greenhouse emissions must stay within a remaining (and quickly declining) carbon budget of 420–570 gigatons of carbon.

If growth in plastic production and incineration continue as predicted, cumulative greenhouse gas emissions by 2050 will be over 56 gigatons CO_2e, or between 10-13 percent of the total remaining carbon budget. As this report was going to press, new research in *Nature Climate Change* reinforced these findings, reaching similar conclusions while applying less conservative assumptions that suggest the impact could be as high as 15 percent by 2050. By 2100, exceed-

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ingly conservative assumptions would result in cumulative carbon emissions of nearly 260 gigatons, or well over half of the carbon budget.

Urgent, Ambitious Action is Necessary to Stop the Climate Impacts of Plastic

This report considers a number of responses to the plastic pollution crisis and evaluates their effectiveness in mitigating the climate, environmental, and health impacts of plastic. There are high-priority actions that would meaningfully reduce greenhouse gas emissions from the plastic lifecycle and also have positive benefits for social or environmental goals. These include:

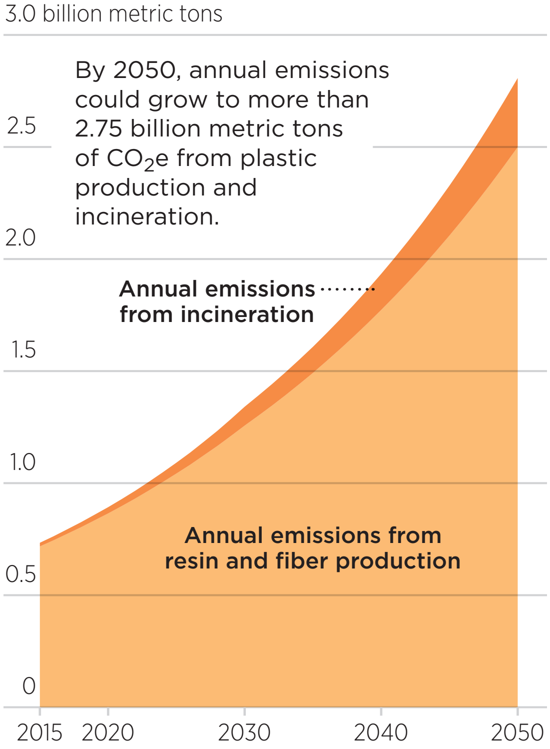
- ending the production and use of single-use, disposable plastic;
- stopping development of new oil, gas, and petrochemical infrastructure;
- fostering the transition to zero-waste communities;
- implementing extended producer responsibility as a critical component of circular economies; and
- adopting and enforcing ambitious targets to reduce greenhouse gas emissions from all sectors, including plastic production.

Complementary interventions may reduce plastic-related greenhouse emissions and reduce environmental and/or health-related impacts from plastic, but fall short of the emissions reductions needed to meet climate targets. For example, using renewable energy sources can reduce energy emissions associated with plastic but will not address the significant process emissions from plastic production, nor will it stop the emissions from plastic waste and pollution. Worse, low-ambition strategies and false solutions (such as bio-based and biodegradable plastic) fail to address, or potentially worsen, the lifecycle greenhouse gas impacts of plastic and may exacerbate other environmental and health impacts.

Ultimately, any solution that reduces plastic production and use is a strong strategy for addressing the climate impacts of the plastic lifecycle. These solutions require urgent support by policymakers and philanthropic funders and action by global grassroots movements. Nothing short of stopping the expansion of petrochemical and plastic production and keeping fossil fuels in the ground will create the surest and most effective reductions in the climate impacts from the plastic lifecycle.

FIGURE 2

Annual Plastic Emissions to 2050



Source: CIEL

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CHAPTER ONE

Introduction

Plastic is one of the most ubiquitous materials in the economy and among the most pervasive and persistent pollutants on Earth. It has become an inescapable part of the material world, flowing constantly through the human experience in everything from plastic bottles, bags, food packaging, and clothing to prosthetics, car parts, and construction materials.

Global production of plastic has increased from two million metric tons (Mt) in 1950 to 380 million Mt in 2015. By the end of 2015, 8,300 million Mt of virgin plastic had been produced, of which roughly two-thirds has been released into the environment and remains there in some form.

In the most general terms, plastics are synthetic organic polymers—giant synthetic molecules comprised of long chains of shorter molecules—derived primarily from fossil fuels. For the sake of simplicity, when this report refers to plastic, it refers to an array of polymers and products with different chemical compositions.

Because plastic does not break down in the environment, it has continued to accumulate in waterways, agricultural soils, rivers, and the ocean for decades. The last few years have seen a growing awareness of and concern about the urgent crisis of plastic in the oceans. More recently, that concern has expanded to the impact of plastic on ecosystems, on food and water supplies, and on human health, amidst emerging evidence that plastic is accumulating not only in our environment but also in our bodies.[1] Amidst this growing concern, there is another largely hidden dimension of the plastic crisis: plastic's contribution to global greenhouse gas emissions and climate change.

As global reliance on fossil fuels declines and plastic production rapidly expands, that emissions impact is poised to grow dramatically in the years ahead. Yet the true dimensions of plastic's contribution to the climate crisis remain poorly understood, creating significant uncertainties that threaten global efforts to avoid the most catastrophic impacts of climate change.

Because plastic does not break down in the environment, it has continued to accumulate in waterways, agricultural soils, rivers, and the ocean for decades. Amidst this concern, there's another largely hidden dimension of the plastic crisis: plastic's contribution to global greenhouse gas emissions and climate change.

In the 2015 Paris Climate Agreement, the world committed to work together to limit total global temperature rise to well below 2 degrees Celsius (°C) and pursue efforts to stay below 1.5°C. In October 2018, the Intergovernmental Panel on Climate Change (IPCC) further highlighted the profound risks to humanity and the environment if warming goes above 1.5°C. To prevent these risks, the IPCC cautioned that we must transition rapidly away from the fossil fuel economy and reduce emissions by 45 percent by 2030 and to net zero by 2050. Efforts to achieve this goal and the strategies to do so have focused overwhelmingly on transforming energy and transportation systems, which account for 39 percent of annual global greenhouse gas emissions. Both of these transitions are important. At the same time, emissions from the industrial sector, which represent 30–40 percent of total global greenhouse gas emissions every year, have received much less attention.

Opposite: © Nick Lund, NPCA/FrackTracker Alliance

Meeting these climate targets will demand dramatic emissions reductions in this sector as well. This report documents how plastic is among the most significant and rapidly growing sources of industrial greenhouse gas emissions. Emissions from plastic emerge not only from the production and manufacture of plastic itself, but from *every* stage in the plastic lifecycle—from the extraction and transport of the fossil fuels that are the primary feedstocks for plastic, to refining and manufacturing, to waste management, to the plastic that enters the environment.

This report examines the sources and scale of greenhouse gas emissions across the plastic lifecycle. It builds on previous efforts to estimate plastic's contributions to climate change, analyzes gaps in those previous efforts, and takes a first step toward identifying what is known and what remains to be analyzed about the links between plastic and climate change. This report pays particular attention to the lifecycle emissions impacts of single-use, disposable plastic found in plastic packaging and an array of fast-moving consumer goods because these form the largest and most rapidly growing segment of the plastic economy.

© Soojung Do/Greenpeace

To calculate these climate impacts, the research begins not in the oceans, but in the oil fields and at the fracking drillpads where plastic begins its life. Over 99 percent of plastic is derived from fossil fuels; accordingly, plastic lifecycle emissions start with the extraction of its fundamental feedstocks (Chapter 4). This report tracks those feedstocks through the pipelines to the refineries and crackers where oil, gas, and coal are converted from fossil fuels into fossil plastic. Greenhouse gases are emitted in the production of plastic resins and, although information is limited, in the creation of products from those resins (Chapter 5). The climate impacts of plastic do not stop when plastic is discarded. Indeed, the vast majority of plastic's lifespan, and a large part of its climate impacts, occur only after its useful life ends. This next stage of life includes the impact of various disposal methods for plastic, including incineration and waste-to-energy processes (Chapter 6). Finally, this report examines what is known about the greenhouse gas impacts of plastic once it leaks into the environment, reviewing early research showing that plastic continues to emit greenhouse gases as it breaks down in the oceans, on shorelines, and on land (Chapter 7). This chapter also examines the potential impacts of microplastics on the ocean's ability to absorb carbon dioxide and store it deep in the ocean depths.

While much of this report builds on what is already known about plastic's climate impacts at disparate moments in the plastic lifecycle, it also highlights the critical gaps and areas where more research is needed to fully understand those impacts. For example, there are substantial gaps in reporting that make estimating the total global emissions associated with specific and important parts of the plastic lifecycle a challenge. Where global figures exist, this report uses them. Despite the limitations in data, this report concludes that the climate impacts of plastic throughout its lifecycle are overwhelming and require urgent, ambitious action.

This report focuses particular attention on the greenhouse gas emissions associated with plastic production and the petrochemical infrastructure

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buildout fueled by the hydraulic fracturing (fracking) boom in the United States. It does so for three reasons. First, the statistics associated with oil and gas extraction in the United States are better defined than for many other aspects of the plastic lifecycle globally. Second, the US fracking boom and the associated petrochemical buildout will be a major driver of plastic production and related greenhouse gas emissions in the decades to come. Finally, the fracking-based model of plastic production is rapidly being exported to other countries around the world.

The final chapter of this report evaluates the solutions that have been proposed to address the climate impacts of plastic. It highlights those solutions that offer the greatest promise and potential benefits for both the climate and the environment, identifies others that may benefit the climate or the environment but perhaps not both, identifies low-ambition solutions that do not address the problem at the scale and speed the climate crisis demands, and exposes false solutions that will be detrimental for the climate, human health, and ecosystems.

These problems have not only a common cause but a common solution: the urgent and complete transition away from the fossil economy and the pervasive disposable plastic that is a ubiquitous part of it.

This report is offered as a first step toward what must be a larger, urgent dialogue about the role of the plastic lifecycle in the climate crisis. It builds on the recognition that, whether one considers plastic's impact on the oceans, on human health, or on the climate, these are all interwoven pieces of the same story. Unsurprisingly, therefore, these problems have not only a common cause but a common solution: the urgent and complete transition away from the fossil economy and the pervasive disposable plastic that is a ubiquitous part of it.

CHAPTER TWO

Metholodogy

Plastic production is among the largest contributors to global greenhouse gas emissions from the industrial sector. The greenhouse gas impacts of plastic production and use are poised to grow dramatically in the coming years, driven by the ongoing rapid expansion of plastic production infrastructure—and the ongoing expansion in natural gas production that is fueling that plastic boom. Both the present scale and anticipated growth of these emissions have significant implications for humanity's efforts to rapidly reduce such emissions and avoid the most catastrophic impacts of global temperature rise.

Despite its importance to the climate debate, however, the climate impacts of plastic production, use, and disposal remain poorly understood by the general public. While a handful of studies have attempted to quantify or estimate greenhouse gas impacts associated with plastic, none has examined those impacts across the full plastic lifecycle, including plastic in the environment. Moreover, and discussed more fully in the following chapters, these gaps in coverage are compounded by limitations of the available data with respect to important emissions sources at each stage in that lifecycle.

The present report attempts to identify these gaps and, to the extent feasible, quantify or estimate the emissions hidden therein. It acknowledges and builds on existing research in the field by providing the most comprehensive snapshot of the direct and indirect sources of greenhouse gas emissions released at each stage of production for the seven types of plastic most commonly found in single-use plastic products. The report does not capture the impact of emissions sources from the broader class of petrochemicals, including fillers, plasticizers, and additives, some of which are introduced in the manufacturing of single-use plastic. Where detailed data are lacking at the global level for key segments of the plastic lifecycle, the report draws on relevant estimates from national or regional sources.

Comprehensive technical analysis is limited by uneven and often unavailable data. For example, the National Emissions Inventory (NEI), compiled by the US Environmental Protection Agency (USEPA), has a nearly comprehensive list of emissions from point sources such as compressor and metering stations. However, carbon dioxide (CO_2), methane (CH_4), and other greenhouse gases are not included in their inventories, making a comprehensive evaluation of their greenhouse gas contributions using the NEI difficult. As a result of data gaps like this in the sources used in the present report, the emissions estimates in this report are likely to underrepresent the full emissions profile of the plastic lifecycle.

Additionally, this report adopts capacity-growth projections for plastic as a data point for additional sources of CO_2 emissions, but the relationship between capacity and actual production is an imperfect measurement for future emissions. The scale of the projected expansion of petrochemical infrastructure and the concerns about its detrimental impacts to environmental integrity and human health warrant policy interventions to ensure more comparable and robust data collection standards and access.

At each stage of the plastic lifecycle, direct and indirect emissions vary according to the raw materials—typically oil, gas, and coal—and the inputs for electricity generation used.[2] This report focuses on emissions estimates associated with the plastic production boom in the United States

Opposite: © Paul Langrock/Greenpeace

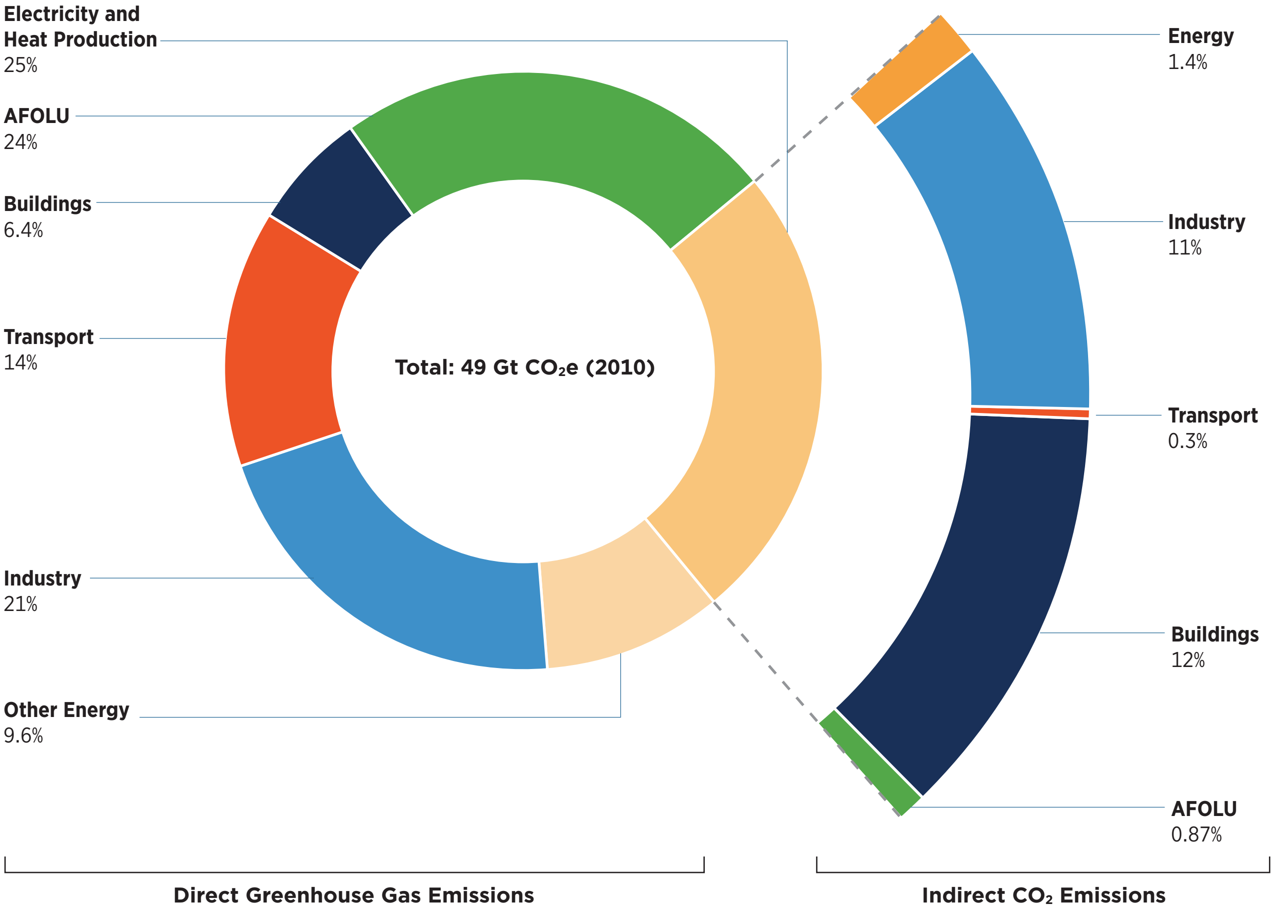
that is fueled by the availability and accessibility of shale gas. As a result, this report focuses on estimates of carbon dioxide equivalents from activities relevant to the extraction of shale gas by fracking; the transportation, storage, and refining of natural gas liquids; the manufacturing of plastic; waste management; and plastic in the environment. The report does not estimate emissions released in the use of plastic products nor does it estimate the full emissions profile of every type of plastic produced. To emphasize the impacts of the plastic lifecycle on climate change, the report highlights the largest sources of atmospheric greenhouse gases emitted to the exclusion of non-greenhouse gas air and water emissions and pollutants.

CO_2 and water vapor are the most abundant greenhouse gases, though there is a wide array of other gases, like methane, and processes that also contribute to atmospheric warming and climate change. To allow greenhouse gases and other climate-forcing agents with dissimilar characteristics to be represented on a comparable footing, climate scientists calculate their impact relative to a common baseline: the CO_2 equivalent (CO_2e).[3] Water vapor is excluded and considered a feedback for purposes of climate models.

This report adopts the methodology for measuring and collecting estimates of greenhouse gases as set forth by the IPCC's 2013 Fifth Assessment

FIGURE 3

Greenhouse Gas Emissions by Economic Sectors



Total anthropogenic greenhouse gas emissions (gigaton of CO_2e per year, greenhouse gas) from economic sectors in 2010. The circle shows the shares of direct GHG emissions (in percent of total anthropogenic greenhouse gas emissions) from five economic sectors in 2010. The pull-out shows how shares of indirect CO_2 emissions (in percent of total anthropogenic greenhouse gas emissions) from electricity and heat production are attributed to sectors of final energy use. "Other energy" refers to all sources in the energy sector, other than electricity and heat productions. The emission data on agriculture, forestry, and other land use (AFOLU) includes land-based CO_2 emissions from forest fires, peat fires, and peat decay that approximate to net CO_2 flux from the sub-sectors of forestry and other land use (FOLU). Emissions are converted into CO_2e based on 100-year Global Warming Potential (GWP_{100}), taken from the IPCC Second Assessment Report.

Source: IPCC, *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* 47 (Core Writing Team, R.K. Pachauri and L.A. Meyer eds, 2014), *https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf*.

Report (AR5) to identify greenhouse gases with varying climate-forcing impacts at each stage of the plastic lifecycle on comparable footing.[4] The AR5 modeled cumulative CO_2 emissions from a common starting point and over a period of 100 years, factoring in the ratio of radiative forcing of one kilogram (Kg) greenhouse gas emitted to the atmosphere to that from one kg CO_2 over the same period of time.[5] In certain instances, values from other IPCC reports, including the IPCC Second Assessment Report (SAR) and the Fourth Assessment Report (AR4), are included in this report where industry's permit data filed to USEPA or US state environmental agencies references those methodologies for reporting on emissions estimates.

This report relies on several frameworks for understanding the quantity of anthropogenic greenhouse gas emissions relative to the likelihood of attaining optimal climate stabilization targets. The IPCC has developed several scenarios to highlight the sources of emissions and modeled reduction targets to limit the concentrations of greenhouse gases to achieve climate stabilization targets. This report also uses the framework of a carbon budget to provide context for the emissions estimates collected at each stage of the plastic lifecycle. A number of institutions, including International Energy Agency (IEA), the IPCC, and Carbon Tracker, among others, have developed climate models to determine the cumulative amount of carbon dioxide emissions permissible over a period of time to keep within a certain temperature threshold.[6]

In October 2018, the IPCC released its Special Report on 1.5°C (SR 1.5), confirming the world has already warmed by more than 1°C, bringing with it dramatic changes to ecosystems, weather patterns, extreme weather events, and communities around the world. Continued warming to 1.5°C will exacerbate these problems, resulting in even more frequent and severe extreme weather events, greater impacts on marine and terrestrial ecosystems around world, and increased impacts on human society. The IPCC issued its clearest warning yet that allowing warming of 2°C will lead to still greater extreme weather events and even more catastrophic impacts.

BOX 1

Greenhouse Gas Emissions

Carbon dioxide equivalents are an emissions metric that factors in different characteristics of varying greenhouse gases and other climate-forcing agents so that they can be compared. Each greenhouse gas has a different global warming potential over 100 years (GWP_{100}), the measure of how much heat a greenhouse gas puts into the atmosphere and how long it persists in the atmosphere.[7]

The three main greenhouse gases (excluding water vapor) and their GWP_{100} compared to carbon dioxide are:[8]

1 x	**carbon dioxide (CO_2)**
28 x	**methane (CH_4) – Releasing 1 Mt CH_4 into the atmosphere is equivalent to releasing 28 Mt CO_2**
265 x	**nitrous oxide (N_2O) – Releasing 1 Mt N_2O into the atmosphere is equivalent to releasing 265 Mt CO_2**

There are other greenhouse gases that have far greater global warming potentials but are much less prevalent, for example, sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs).

TABLE 1

Global Warming Potentials of Greenhouse Gases

Predominant greenhouse gases (along with water vapor) and their global warming potential (GWP) compared to carbon dioxide		
Greenhouse Gases	**Cumulative forcing over 20 years (GWP_{20})**	**Cumulative forcing over 100 years (GWP_{100})**
Carbon Dioxide, CO_2	1	1
Methane, CH_4	84	28
Nitrous Oxide, N_2O	264	265
Tetrafluoromethane, CF_4	4,880	6,630
Fluorinated Gases: hydroflurocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)	506	138

Source: IPCC, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change 47 (Core Writing Team, R.K. Pachauri and L.A. Meyer eds, 2014), *https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf*.

The IPCC concluded that keeping warming to no more than 1.5°C is both necessary and achievable, but it emphasized that to do so requires rapid and dramatic reductions in greenhouse gas emissions. Specifically, it requires cutting greenhouse gas emissions 45 percent by 2030 and reaching net-zero emissions by no later than 2050.[9] While SR 1.5 concluded that reducing the carbon intensity of electricity generation is a key component of cost-effective mitigation strategies in achieving direct CO_2 emissions reductions, a focus on how to best reduce emissions from the electricity and transportation sectors alone is not sufficient to reach the 1.5°C target by 2100.

CHAPTER THREE

Calculating the Climate Costs of Plastic

ESTIMATES OF CRADLE-TO-RESIN EMISSIONS RATES

This report builds on earlier attempts to identify and quantify the climate impacts of plastic.

A 2011 analysis from Franklin Associates prepared for the American Chemistry Council examined the cradle-to-resin greenhouse gas emissions for the major plastic resins. Cradle-to-resin estimates include emissions from oil and gas extraction through resin production. Franklin Associates' estimates underwent peer review before publication in the US Department of Energy's National Renewable Energy Laboratory's Life Cycle Inventory Database. Their conclusions are based on average direct emissions and energy use reported by 17 companies that operate 80 plants in North America, though industry coverage varies by resin. Since 2011, several peer-reviewed studies have examined these estimates and used them to estimate the potential impact of more sustainable alternatives. One study from Posen et al. combined the original work by Franklin Associates and other analyses to produce midpoint estimates for cradle-to-resin emissions intensities for North American plastic production. These estimates are incorporated into this analysis.

PlasticsEurope, the European industry association for the plastic industry, hosts "Eco Profiles" of various plastics, which are also cradle-to-resin estimates of emissions intensity for different plastic resins. Whereas Posen et al. focused on North American plastic production, PlasticsEurope Eco Profiles correspond to European plastic production. Notably, the emissions estimates for European plastic production are greater than North-American-made plastic, for reasons that will be discussed in greater detail in the following chapters.

These two cradle-to-resin estimates inform this report's evaluation of the likely minimum emissions from the first stages of the plastic lifecycle (extraction, transport, refining, and manufacture). As the following chapters describe in greater detail, these estimates are subject to substantial undercounting of emissions. This report will identify sources of greenhouse gases that are as yet uncounted or unquantified but are nonetheless significant contributors to the overall greenhouse gas impact of the plastic lifecycle.

For the purpose of comparing emissions over time to the constraints of global carbon budgets, this report will use an adjusted weighted average of these cradle-to-resin estimates, building in conservative assumptions that are likely to reduce the apparent climate impact of the plastic lifecycle. Specifically, the estimates of cradle-to-resin greenhouse gas intensity from both Posen et al. and PlasticsEurope are averaged for the primary plastic resins polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polystyrene (PS). These five thermoplastics represent at least 85 percent of all plastic production and are less carbon-intense to produce than more uncommon types of plastic, though still responsible for significant carbon emissions. As such, using this lower estimate for all plastic production is likely to underrepresent the true emissions impacts from the growth of plastic production over time. However, without knowing the relative growth rate of niche plastics versus primary plastics, this bias ensures that cradle-to-resin emissions used for the sake of carbon-budget analysis represent likely emissions minimums.

Because North American plastic production primarily uses natural-gas-sourced ethane as a

Opposite: © iStockphoto/Marke Trawcinski

© Carroll Muffett/CIEL

feedstock, and European plastic production primarily uses oil-sourced naphtha, a combination of estimates provides a better representation of global production. There is no reason to believe that plastic produced in other regions is substantially less emissions-intense than plastic produced in Europe and North America. Moreover, known processes that rely on coal feedstocks are considerably more emissions-intensive than plastic production using oil or natural gas feedstocks. These coal-to-olefin processes are a small but growing share of global plastic production, and there are no reliable projections for coal-to-olefin's share of plastic production in decades to come. As a result of these data gaps, the estimates in this report do not reflect the increased emissions from the enormously carbon-intense coal-to-olefins processes and applies only the lower cradle-to-resin profile of North American and European plastic. Based on the calculations described above, this report assumes 1.89 Mt CO_2e are emitted per Mt plastic resin produced.[10]

A significant component of cradle-to-resin emissions for plastic derives from the electricity and heat that power production processes, because that electricity and heat is produced almost exclusively by the combustion of fossil fuels. As discussed in greater detail below, such processes may be performed with renewable or low-carbon energy sources, reducing the carbon intensity of one stage in the plastic production process. Both Posen et al. and Material Economics, incorporating PlasticsEurope Eco Profiles, produce estimates for the carbon intensity of resin production using low-carbon energy. Using the same process to average estimates for North America and Europe, this report assumes an average cradle-to-resin carbon intensity for plastic produced with low-carbon or renewable energy sources at 0.90 Mt CO_2e per Mt of plastic produced.

There are strong reasons to doubt that plastic production will reduce its carbon intensity quickly, even as the electricity grid shifts towards ever greater reliance on renewable and low-carbon energy. Many industrial facilities in the plastic supply chain have on-site power generation for electricity and heat,[11] meaning that an increasingly low-carbon public energy grid may have little bearing on the energy mix used for plastic production, and these sources would need to be converted. Moreover, because fossil fuel production and plastic production are closely linked—with elements of both often taking place at the same or adjacent facilities—the entrenchment of fossil fuels in the plastic production process is even harder to overcome. It is important to note that even if fully powered by renewable energy sources, plastic production would remain a significant source of greenhouse gas emissions because of the significant emissions created by the chemical processes themselves. Fully converting electricity and energy systems to rely on renewables will not address these emissions from plastic production and do not address emissions from end-of-life treatment.

The assumptions described above, coupled with the uncounted emissions described herein, strongly indicate that the true impact of plastic on atmospheric greenhouse gas concentrations is considerably greater than the numeric estimates this report suggests. Nonetheless, the calculable impact is of great concern, and the limiting assumptions only underscore the need for greater attention to plastic's large and rapidly growing climate impacts.

PREVIOUS EFFORTS TO MEASURE PLASTIC'S LIFECYCLE IMPACT

This report also draws on an analysis of present and future plastic lifecycle emissions prepared by the research group Material Economics. Significantly, in its report *The Circular Economy*, Material Economics examines the critical importance of reducing emissions from industrial sources to achieve agreed climate goals.

To reconcile the impacts of the plastic lifecycle with established carbon budgets, Material Economics addresses not only the emissions associated with plastic production itself, but associated emissions from plastic waste and the effect on emissions trajectories from the growth of plastic production through the end of the century. In combination with emissions intensities for plastic resin production based on PlasticEurope's Eco Profiles, Material Economics measures the potential cumulative climate impact of plastic through 2100.

This report builds on Material Economics' analysis in several ways. As described above, this report uses a conservative estimate of global emissions intensity for cradle-to-resin plastic production to account for both geographic differences in plastic feedstocks and the comparatively rapid growth of lower-emission plastic resin types.

For end-of-life plastic, Material Economics uses a gross figure of embedded carbon, the carbon content of solid plastic that could be released into the environment. In the subsequent chapters on Waste Management and Plastic in the Environment, the present report details the pathways through which such embedded carbon may be released into the atmosphere, quantifies the potential scale of those emissions, and highlights significant unknowns and data gaps that may influence and dramatically undervalue those measurements.

The assumptions described here strongly indicate that the true impact of plastic on atmospheric greenhouse gas concentrations is considerably greater than the numeric estimates this report suggests.

This report also assumes growth rates in line with estimates from the World Economic Forum, Mitsubishi Chemical Techno-Research, and analyses of American Chemistry Council data on investment in and growth of plastic and petrochemical production capacity. This growth rate, of 3.8 percent until 2030 and 3.5 percent at least through 2050, is perhaps the biggest indicator of the urgency of understanding the climate impacts of the current and planned expansion of plastic production. Taking into account the speed and scale of the ongoing buildout of plastic infrastructure, the growth rate through 2030 should be considered extremely conservative and is likely a significant underestimate of future growth if industry expansion plans are fully implemented.

PLASTIC PRODUCTION GROWTH ESTIMATES 2015–2100

As noted in the introduction, plastic production is growing rapidly and investments in new capacity have accelerated dramatically in recent years. Accordingly, any projection of the long-term contribution of plastic to greenhouse gas emissions must make assumptions about the pace and scale of this growth.

The World Economic Forum (WEF) projects that plastic production and use will grow 3.8 percent per year through 2030. WEF assumes this rate of growth will slow to 3.5 percent per year from 2030 through 2050.[12] WEF does not provide estimated plastic industry growth rates after 2050. A separate analysis of potential plastic-related emissions prepared by Material Economics takes a different approach, assuming that plastic production will grow at a relatively constant rate of approximately 1.6% from now until 2100.

The present report applies WEF growth estimates on the grounds that these estimates better reflect the available data on current and projected industry growth in the near to medium term. Indeed, there is a strong likelihood that WEF's estimate may understate the actual rate of industry growth, particularly during the critical period between now and 2030.

According to the American Chemistry Council, in the space of one year, the planned investments and the number of new or expanded petrochemical production facilities grew by more than 25 percent.

In September 2017, the Center for International Environmental Law (CIEL) released a report examining how the fracking boom in the United States and beyond is fueling a dramatic buildout of new infrastructure for the production of plastic.[13] In that analysis, CIEL projected that the production capacity for ethylene and propylene—the two most important plastic feedstocks—would grow by 33–36 percent by 2025.[14]

This conclusion was based on an earlier analysis by Mitsubishi Chemical Techno-Research Corporation, which projected a 35 percent growth in ethylene production capacity and a 33 percent growth in propylene production capacity between 2016 and 2025.[15] In the period since Mitsubishi's and CIEL's reports were released, the pace of industry investment in expanding plastic infrastructure has further accelerated. For example, in September 2017, the American Chemistry Council reported a total of $164 billion of investment in 260 new or expanded production facilities for petrochemicals (calculating from a 2010 baseline). By September 2018, it reported total investments of over $200 billion in more than 330 new or expanded facilities. In the space of a year, both the planned investments and the number of new or expanded facilities grew by more than 25 percent.

For some kinds of plastic, the pace of growth is dramatically greater. In February 2018, for example, the *Houston Chronicle* projected that ethane consumption, primarily for use in ethylene, would grow 30 percent by 2019. It reported that "ICIS, a global energy and petrochemical research firm with offices in Houston, has forecast that by 2022, US producers of polyethylene, the most common plastic, will have further increased their production capacity by as much as 75 percent, with much of the new production exported to foreign markets."[16]

In its *Global Ethylene Capacity and Expenditure Outlook* in the fourth quarter of 2018, the research firm Research and Markets projected that global production capacity for ethylene will grow from 180 million Mt in 2017 to 270 million Mt in 2026.[17] A parallel report on propylene projected that capacity will grow from approximately 120 million Mt per year in 2017 to more than 150 by 2026.[18] Combining the figures for ethylene and propylene yields a growth in production capacity of these feedstocks from 300 million tons per year in 2017 to 420 million tons in 2026. This represents a 40 percent growth in production capacity by 2026.

To ensure consistency in calculations, this report assumes that production capacity for key plastic feedstocks will grow by 33–36 percent by 2025. For growth estimates spanning the full period between 2015 to 2050, it applies the growth rates used by WEF. In light of the rapid economic and social transitions necessitated by both the plastic crisis and the climate crisis, this report does not attempt a growth projection for plastic production after 2050. Instead, it assumes that plastic production remains stable from 2050 through 2100. On the basis of the foregoing information, the authors consider each of these growth estimates to be conservative and a likely underestimate of the long-term growth in this industry under business-as-usual scenarios.

ESTIMATING PLASTIC'S IMPACT ON GLOBAL CARBON BUDGETS

Drawing on data from the IPCC AR5 database, Material Economics concluded that to have even a 66 percent chance of keeping warming below 2°C, cumulative emissions from the energy and industrial sectors as a whole cannot exceed 800 gigatons (Gt) by 2100. To have any chance of keeping within 1.5°C, emissions must be lower still, and net global emissions must fall to zero by 2050. An analysis of the IPCC's SR 1.5 report by Carbon Brief concludes that the total remaining carbon budget limit warning to 1.5°C is as little as 420 Gt CO_2e and no more than 570 Gt.[19]

Of the 800 Gt CO_2e carbon budget for energy and industry sectors through 2100 under a 2°C scenario, Material Economics allocates 300 Gt for industry.[20] Industrial sources comprised 40 percent of global greenhouse gas emissions in 2014.[21] Just four sectors—steel, plastic, cement, and aluminum—account for fully three quarters of these emissions. Of the four sectors, plastic is witnessing the most rapid and sustained growth, and it is projected to have the largest growth in emissions under business-as-usual scenarios.[22]

In 2015, 380 million Mt of plastic resins and fibers were produced. Using WEF's growth rate estimates—3.8 percent growth per year through 2030 and 3.5 percent growth per year at least through 2050—annual plastic production in 2050 is expected to reach 1,323 million Mt, or nearly 3.5 times as much as was produced in 2015.

Applying the cradle-to-resin emissions estimate above of 1.89 tons CO_2e/ton of plastic resin produced, plastic production could emit 1.26 Gt CO_2e per year by 2030—equivalent to the emissions from 277 five-hundred-megawatt coal plants. Even assuming the current expansion slows after 2030, annual emissions from plastic production could rise to 2.5 Gt by 2050—emitting as much CO_2 as 549 five-hundred-megawatt coal plants. Cumulative emissions between 2015 and 2050 would exceed 52 Gt, equal to nearly 30 years of emissions from all the coal, gas, and oil plants in the United States.[23] On its present trajectory, plastic production alone could consume more than 12 percent of the earth's remaining carbon budget by 2050 and 111 Gt or more if emissions continue through the end of the century.

Powering energy-intense plastic production processes with 100 percent renewable energy could reduce these production-related emissions by half, but they would not address the significant greenhouse emissions produced by the chemical conversion processes themselves. More importantly, whether and on what timeline such a conversion to renewable energy could be achieved is highly uncertain. Facilities would have to alter their on-site energy production process, and the electricity grid would need to evolve as well. While the latter is already happening to a certain extent, the challenges to the former, as explained above, are substantial.

Projections of this kind are subject to a range of uncertainties, especially as those projections apply further into the future. The scale of the plastic problem is so severe, however, that even conservative projections about emissions from plastic from 2050 to 2100 are dire. For example, even if plastic production stopped growing from 2050 to 2100, and assuming renewable energy were fully integrated into the production process, cradle-to-resin emissions for the second half of the century would still amount to an additional cumulative 59.5 Gt CO_2e by 2100.[24] Assuming any higher level of emissions or a moderate growth rate further accelerates the greenhouse gas impacts.

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Applying conservative growth projections between now and 2050, and assuming production stabilizes and is fueled completely by renewable energy through the latter half of the century, emissions from plastic production alone could generate more than 111 Gt CO_2e by 2100—even before the substantial and growing emissions from plastic waste incineration are taken into account.

As documented in Chapter 6, greenhouse gas emissions from plastic incineration could add another 4.2 Gt CO_2e to the atmosphere by 2050, bringing total emissions production and incineration alone to more than 56 Gt CO_2e. Thus, plastic alone could consume from 10-13 percent of the earth's remaining carbon budget, undermining urgent global efforts to keep warming below 1.5°C and making even a 2°C target nearly impossible.

These projections demonstrate the magnitude of the climate threat posed by the ongoing rapid expansion in plastic production. As the following chapters demonstrate, moreover, the plastics lifecycle includes a wide array of emissions sources and emissions pathways that are almost certainly being overlooked in current assessments of plastic's climate impacts, and in the business and policy decisions based on those assessments.

CHAPTER FOUR

Extraction and Transport

Almost all plastic, including resins, fibers, and additives, is derived from fossil fuels. The molecules or monomers used to make plastic, like ethylene and propylene, are derived from oil, gas, and coal. While not all fossil-fuel-derived chemicals (petrochemicals) become plastic, nearly all plastic begins as fossil fuels.

THE ORIGINS OF PLASTIC: OLEFINS

The process for producing plastic is similar for each feedstock material, though there are important differences. In general, after oil and gas are extracted from wells, they undergo a process to separate them into component parts, some of which are used for plastic production. Those chemical components are sent to facilities, usually “cracking” plants, where they are turned into olefins, organic chemicals that form the base for most plastic. The two most important olefins are ethylene and propylene.

Olefins are monomers, small molecules that can be bound together to make much longer chains. To become plastic, olefins get stitched together to form extremely long chain molecules, or polymers, in a process called polymerization. If necessary, they are also mixed with plasticizers. Then they are cooled and shredded into pellets called nurdles. Those nurdles form the virgin plastic sold to manufacturers, who then melt and reshape those materials into products like bottles, bags, and household items.

Olefins are commodity chemicals, so ethylene made from gas is no different than ethylene made from oil or coal. The process after olefin production, therefore, depends on what is being produced, not upon the feedstock from which the olefin originated. The path from fossil fuel to olefin is different, however, depending on which fossil fuel feedstock is producing the olefin.

Producing Olefins

Oil derivatives are the primary feedstock for plastic production worldwide. After crude oil is extracted from the ground, it is transported to a refinery. The oil refining process produces, among other things, naphtha, a combination of hydrocarbons that can be turned into olefins via a process called steam cracking. Olefins can also be produced directly via fluid catalytic cracking at oil refineries, although this process is less common.

Natural gas is especially important in the production of ethylene. Natural gas is primarily methane, though heavier hydrocarbons in the form of natural gas liquids (NGLs) are produced from gas wells as well. The most common NGL is ethane. Ethane, once separated from the rest of the gas, is processed in a steam cracker to produce ethylene. Whereas steam cracking of naphtha can produce ethylene and propylene, ethane crackers are designed to optimize ethylene production. Propane may also be processed into propylene in separate facilities called propane dehydration plants.

Coal is also used to make olefins, although the process is considerably more expensive and less cost effective than olefins derived from oil and gas. Coal can be turned into synthetic natural gas (syngas) through the process of coal gasification. Once gasified, this syngas, which is methane, can be turned to methanol, which can then be turned into olefins. This process is sometimes called coal-to-olefins or methanol-to-olefins.[25]

Whether olefin producers use oil, gas, or coal as a feedstock depends on cost and availability. Companies in the Middle East and North America rely primarily on ethane from natural gas, whereas producers in Europe and Asia rely primarily on oil, with some in China also relying on coal.[26]

Opposite: © FrackTracker Alliance

BOX 2

Plastic Resins

Mass-produced plastic includes polymer resins, synthetic fibers, and additives. While there are many kinds of plastic, the most prevalent resins and fibers include PE, PP, PET, PVC, PS, and polyurethane (PUR) resins; and polyester, polyamide, and acrylic (PP&A) fibers. The largest group of non-fiber plastic production (PE, PP, PET, PVC, and PS) constitute over 85 percent of all plastic produced by weight.[27] Understanding these materials and their supply chains is critical to understanding not only the greenhouse gas emissions traceable to single-use plastic and plastic packaging, but also the impacts of plastic in general.

PE accounts for 36.3 percent of all plastic produced.[28] It is often segmented into high-density polyethylene (HDPE) and low-density polyethylene (LDPE), as well as sometimes linear low-density polyethylene (LLDPE), which have different applications. HDPE is used for products like milk and shampoo bottles, pipes, and houseware, while LDPE is used to make products such as plastic bags, food packaging films, and various kinds of trays and containers.[29] In both cases, packaging makes up the largest single-use category of polyethylene use.[30]

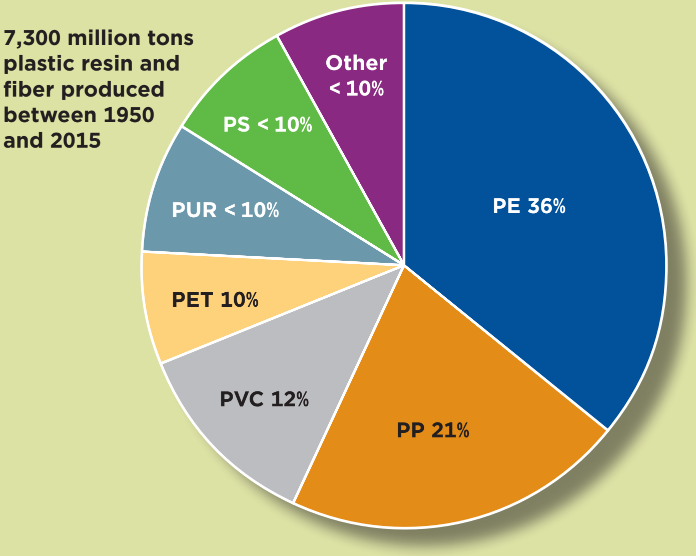
PP accounts for 21 percent of plastic produced.[31] PP is used for food packaging, snack and candy wrapping, and microwavable containers, among other uses.[32] Similar to PE, packaging represents the largest single-use category for polypropylene.[33]

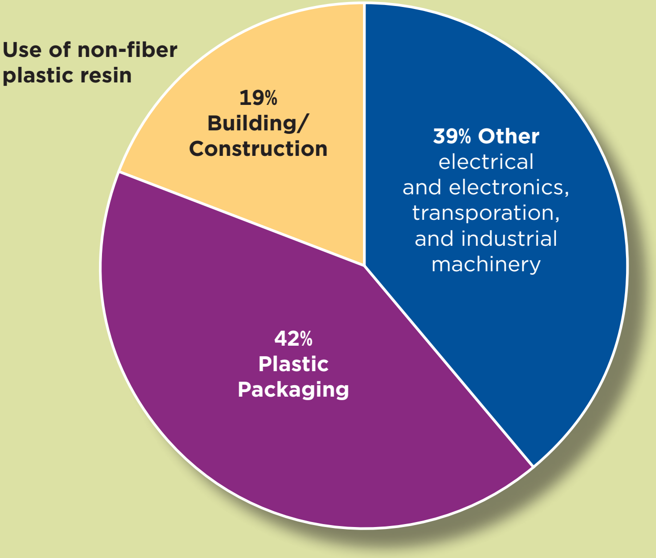
PVC accounts for 11.8 percent of plastic produced.[34] While it is used in packaging, PVC is primarily used as a building and construction material, and it is found in pipes, window frames, and floor and wall coverings, among other uses.[35]

PET accounts for 10.2 percent of plastic produced. PET is nearly exclusively used for plastic packaging, particularly in water bottles, soft drinks, and cleaning products.[36]

FIGURE 4

Common Plastics and their Uses





Source: Roland Geyer, Jenna R. Jambeck and Kara Lavender, Law, Production, use, and fate of all plastics ever made.

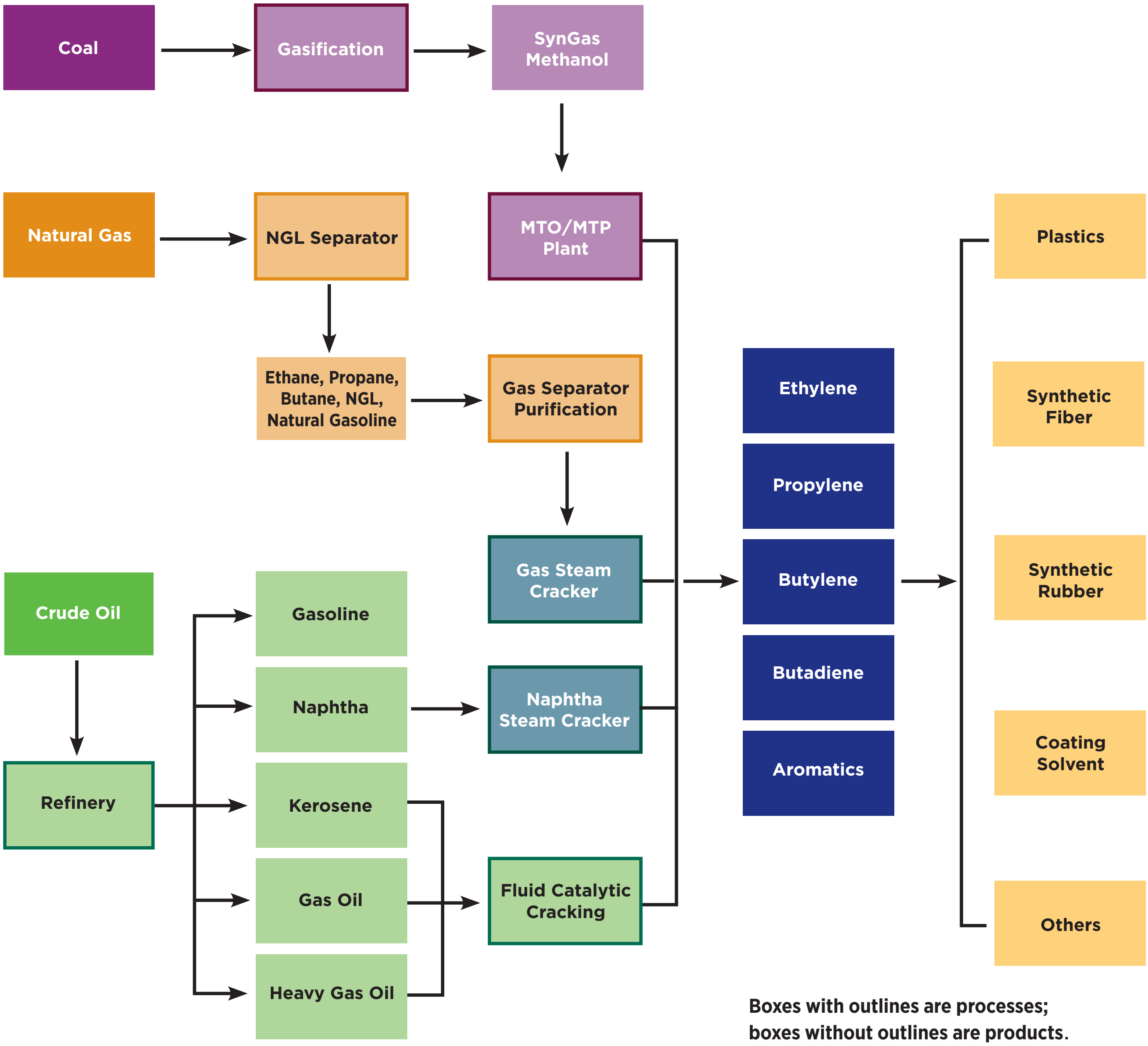
Finally, PS accounts for 7.6 percent of plastic produced. Polystyrene is used for products like glasses frames and cups. It is more familiar in its expanded form, expanded polystyrene (EPS), commonly misidentified as the brand name Styrofoam, which is used for items such as cups, food trays, and cushioning material.[37]

The Growth of Petrochemical Production

Analyses of the plastic and petrochemical industries are largely consistent in forecasting significant growth in both production and consumption of plastic over the next several decades. WEF predicts growth in plastic production of 3.5–3.8 percent per year through 2050.[38] Material Economics projects plastic production to more than double, from just over 320 million Mt per year in 2015 to over 800 million Mt per year by 2050.[39] IEA predicts slightly slower growth, but still projects a nearly 70 percent increase in key thermoplastic production between 2017 and 2050.[40] Consistent with the growth in plastic production, estimates from Mitsubishi Chemical Techno-Research project growth in the production of ethylene and propylene, the key feedstocks for the main thermoplastics, of 2.6 percent and 4.0 percent per year, respectively, through 2025.[41]

FIGURE 5

Petrochemical Products from Various Feedstocks



Boxes with outlines are processes; boxes without outlines are products.

Source: Presentation, Mitsubishi Chemical Techno-Research, Global Supply and Demand of Petrochemical Products relied on LPG as Feedstock (Mar. 7, 2017) (on file with authors).

These projections not only forecast an impending acceleration of plastic production and waste, but also underscore the importance of growing plastic production as a driver of increased fossil fuel demand. According to WEF, plastic production accounts for 4–8 percent of global oil consumption annually, with roughly half used for material feedstock and half used for energy in the production process.[42] WEF estimates that, if growth trends continue, plastic will account for 20 percent of global oil consumption by 2050.[43] IEA's *The Future of Petrochemicals* report predicts that petrochemicals will account for more than a third of oil production growth through 2030 and more than half of oil production growth through 2050.[44]

If growth trends continue, plastic will account for 20 percent of global oil consumption by 2050.

BOX 3

The Truth about Bioplastic

Bioplastic—or biopolymers—is distinct from conventional plastic because it is made from renewable plant feedstocks such as corn, cassava, sugar beet, or sugar cane and not petrochemicals. Some products labeled as bioplastic contain a combination of plant-based and petrochemical feedstocks. Bioplastic can be as versatile as conventional plastic and is used to manufacture a variety of commercial products. Food-packaging uses include coffee cups, bottles, plates, cutlery, and vegetable bags; medical applications include surgical sutures, implants, and fracture fixation; other commercial applications include fabrics. Bioplastic includes polylactic acid (PLA), plant-derived PET, and polyhydroxyalkanoate (PHA) and can be mixtures of biopolymers, petrochemical-derived plastic, and fibers.

Bioplastic is not inherently biodegradable. The material used in plant-based PET is indistinguishable from its petrochemical equivalent. Plant-based PET, like petrochemical PET, will not decompose, but it can be recycled with conventional PET. Plant-derived PET thus has the same environmental impact as conventional plastic through its use and end of life. PLA is not suitable for home composting; biodegradation requires an industrial composting process that uses high temperatures (over 58˚C) and 50 percent relative humidity (most home composters operate at less than 60˚C and only rarely reach temperatures greater than this).

Pure bioplastic will release carbon dioxide (or methane) and water when it breaks down. However, if additives or toxins have been added during the manufacturing process, as is generally the case, these may be released during degradation. As with fossil-fuel-based plastic, chemicals may be added to a bioplastic to add strength, prevent wrinkling, or confer breathability. Further research and lifecycle analyses will help to understand the role and impacts of different bioplastics.

Plastic production is expected to grow for decades, and those projections extend further into the future than current plans to construct new petrochemical and plastic production facilities. Current plans for rapid expansion of production capacity are concentrated in the United States, China, and the Middle East, but also include expansions of petrochemical capacity in Europe and South America.

As a result of the shale gas boom in the United States, firms are investing heavily in new production capacity near shale formations. As of September 2018, projected investments in US petrochemical buildout linked to fracked shale gas amounted to over $202 billion for 333 new facilities or expansion projects.[45]

The fracking boom in the United States has led suppliers to seek long-term supply contracts and export oversupplied gas. Liquefied natural gas (LNG) facilities—and the pipelines, coastal terminals, and ships that service them—have accordingly become a growing component of fracking infrastructure to support these efforts.

This internationalization of the fracking boom has already started and is set to accelerate. In Argentina's Vaca Muerta region, oil, gas, and petrochemical companies are working to open the second-largest fracking frontier on the planet and attract major petrochemical investments to exploit the fracked gas. In July 2017, the United Kingdom received its first delivery of LNG from the Sabine Pass export terminal in the US state of Louisiana. The Cove Point LNG export facility in Maryland is now a point of transport for Marcellus Shale gas destined for Japan and India. As of the drafting of this report, five additional LNG export terminals are in the planning stages in the United States.[46]

GREENHOUSE GAS EMISSIONS FROM OIL AND GAS FEEDSTOCKS

The extraction and transport analysis in this report focuses primarily on emissions from the

US natural gas sector. This focus ensured that a robust profile of emissions could be produced, whereas limitations in data access and variability in regional emissions data would make such global measurements extremely difficult. Nonetheless, a description of the global oil market and its emissions is warranted to provide a rough estimate of the scale of emissions from oil production, as well as an understanding of the limitations in constructing emissions analyses.

The CO_2e emissions per barrel of oil produced varies greatly between sources of oil. According to a 2015 report from the Carnegie Endowment for International Peace, the carbon intensity of oil can vary by over 80 percent per barrel between the lowest- and highest-emitting oils.[47] A recent analysis of nearly 9,000 oil fields determined a weighted-average carbon intensity for "well-to-refinery" oil production and concluded that global well-to-refinery emissions in 2015 were approximately 1.7 Gt CO_2e.[48] Apportioned for the approximately four percent of oil used as chemical feedstock for plastic,[49] an estimate of 68 million Mt CO_2e can be produced for the contribution of emissions from oil production to plastic production in 2015.

This estimate has significant limitations, however. While it is true that approximately four percent of oil is used as material feedstock for plastic production, that contribution is not distributed evenly. The carbon intensity of the specific oil sourced will affect the carbon intensity of the subsequent plastic produced, and as noted earlier, that carbon intensity can vary greatly. Moreover, because crude oil is widely traded, plastic production and oil production are not as geographically tied as is the production of plastic from natural gas. Nonetheless, while this estimate should not be relied on for formal greenhouse gas accounting, it demonstrates the scale of emissions from plastic production.

After extraction and transportation, oil is refined. The refining process produces naphtha, which can then be cracked to produce olefins for plastic production, and may also directly produce olefins through the fluid catalytic cracking of lighter elements in the oil. Global emissions from steam cracking for both ethane and naphtha are addressed in the next section.

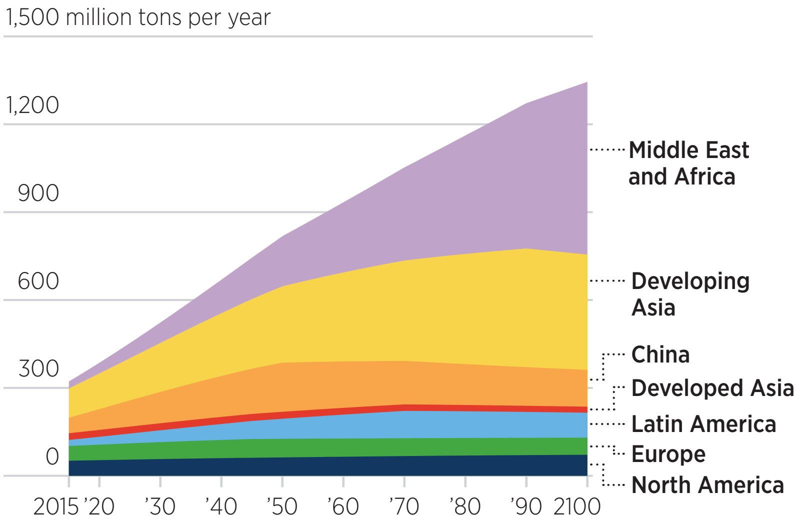
Calculating the exact greenhouse gas emissions from oil refining is challenging, but estimates may be made. One from Moody's places greenhouse

FIGURE 6

Plastic Production Will Increase Significantly

Projections based on business-as-usual growth predict markedly increased plastic use through 2100.

Plastics Demand by Region, 2015 to 2100



Source: Material Economics, The Circular Economy (2018).

BOX 4

Coal-to-Chemicals and Greenhouse Gas Emissions

It is possible to make olefins, the base chemicals for plastic production, from coal feedstocks. This process is sometimes called coal-to-olefins, coal-to-chemical, or methanol-to-olefins (as methanol is often made from coal feedstocks). This process is typically not cost competitive with plastic production from oil or gas feedstocks and is only used in China.

Converting coal into methanol and subsequently converting methanol into olefins is an extremely energy-, water-, and emissions-intense process. Ethane and naphtha cracking release 1.0–1.2 and 1.6–1.8 Mt CO_2e per Mt olefin produced, respectively. According to an estimate from HSBC Bank, coal-to-olefins processes, in contrast, emit 7.1–10.6 Mt CO_2 per Mt of olefin produced.[50] It is unsurprising, then, that Olivier Thorel, an executive at Shell Chemicals, described the process as "massive CO_2 machines that make chemicals as a sidestream."[51]

The future of the coal-to-olefins process is not clear. Massive investments in new coal-to-olefins capacity have been announced, although competing shipments of US natural gas and naphtha feedstocks may affect those plans. Either way, this form of producing plastic is a profound climate problem above and beyond the already problematic lifecycle of plastic produced from oil or gas. From a climate, energy-use, and water-use perspective, preventing the construction of additional coal-to-olefins production plants should be a high priority.

gas emissions from oil refining at approximately one Gt CO_2e per year.[52] This appears consistent with other estimates measuring the carbon intensity of refining or the emissions from refining in one region.[53] Applying the same four percent attribution ratio as above, emissions of approximately 40 million Mt CO_2e per year may be applied to plastic production.

This report estimates that 12.5–13.5 million Mt CO_2e are emitted per year by the extraction and transportation of natural gas in the United States for the creation of plastic feedstocks.

Again, this estimate is subject to significant uncertainty. Emissions vary by refinery and kind of oil refined, and it is beyond the scope of this report to try to trace emissions with that degree of specificity. Still, it is possible to produce a reasonably reliable present estimate of emissions from oil production and refining attributable to plastic production, at 108 million Mt CO_2e per year. Conservative assumptions built into the estimates here suggest no reason to believe the actual number is materially smaller; to the contrary, the actual number may be considerably larger.

Additional emissions from natural gas extraction and transformation in the Middle East, which primarily uses ethane for plastic production, are omitted from this analysis due to the inaccessibility of adequate data. Nonetheless, those emissions are not insignificant and should be understood as an additional element of the greenhouse gas impact of plastic production.

The next several sections identify and quantify the various sources of emissions from the natural gas production and transportation process in the United States and apportion those emissions to plastic production.

NATURAL GAS IN THE UNITED STATES

Plastic can be made from a variety of hydrocarbon feedstocks,[54] but one of the principal raw materials begins with ethane gas that produces ethylene through steam cracking.[55] After methane, ethane is usually the most common component of natural gas. It is considered a natural gas liquid; natural gas high in NGLs is called “wet gas.” According to IEA, natural gas in the US accounts for around 40 percent of global capacity to produce low-cost ethane, and the fracking boom in the United States led to increases in the US share of ethane-based chemical exports globally.[56]

Although Saudi Arabia and Iran are significant producers of petrochemicals sourced from ethane, there is not much publicly available information from those and other Middle Eastern countries. In contrast, the available information from the US shale gas boom provides a useful look into the greenhouse gas emissions from the first stages of the plastic lifecycle.[57]

The oil and gas industry is the largest industrial source of methane emissions, according to the USEPA.[58] Estimating the portion of greenhouse gas emissions from the gas industry attributable to the production of plastic requires making several assumptions due to industry variability, demand-side fluctuations, and numerous data gaps. However, because approximately 4.2 percent of the natural gas stream is composed of ethane, and 44 percent of ethane is used for petrochemical production, 1.8 percent of emissions from the natural gas production process will be applied to the plastic lifecycle. This report estimates that 9.5-10.5 million Mt CO_2e are emitted per year by the extraction and transportation of natural gas in the United States for the creation of plastic feedstocks.

Ethane Production Estimates

In 2015, 790,968 active oil and gas wells in the US produced over 32.9 trillion cubic feet of natural gas. Some of the ethane from the natural gas remains in the natural gas stream to be burned by industrial, commercial, and residential consumers in a process known as ethane rejection.[59] This practice is likely to increase as new pipelines and crackers come online and more ethane can be used.

It is impossible to say at this time exactly how much ethane comes out of the ground in the United States because of ethane rejection and the high variability of ethane in different oil and gas formations.[60] Union Gas, a supplier that receives gas from Canadian and American wells, however, indicates that ethane comprises between 1.5 and nine percent of natural gas, with an average of 4.2 percent.[61] Applying that figure to total gas production results in an estimate of around 1.34 trillion cubic feet of ethane (or 934 million 42-gallon barrels) produced in the United States in 2015.[62]

© Garth Lenz/iLCP

The amount of NGLs produced at gas facilities in the United States has nearly doubled to more than 1.2 billion barrels in the ten years between 2005 and 2015, mainly due to large increases in production from shale gas and tight oil formations.[63] Ethane is the most common of these NGLs, accounting for 412 million barrels in 2015.[64] Using the Union Gas estimate of natural gas containing 4.2 percent ethane,[65] about 44 percent of the ethane produced is used as a plastic feedstock, totaling 589.6 million cubic feet (MMcf) of used ethane—with the balance rejected into the natural gas stream, vented, flared, or wasted in some other fashion.

Globally, 134 million Mt of ethylene were produced in 2014, including 25 million Mt in the United States.[66] Propylene, the second most common petrochemical feedstock after ethylene, had an estimated production of 89 million Mt in 2014 and is the source of polypropylene plastic.[67] Such plastic is co-produced at some petrochemical cracker facilities, along with smaller amounts of polybutylene from butane feedstocks.[68]

As noted above, this report apportions just 1.8 percent of greenhouse gas emissions from natural gas production to the development of plastic. As new NGL pipelines and facilities are built, however, this percentage is expected to rise, as less ethane is rejected into the natural gas stream, flared, or vented. Additionally, many industry analysts[69] consider the development of NGLs to be a driving force in the extraction industry. High production values in recent years have meant that natural gas prices remain low[70] as supplies remain strong. Now, NGL prices are rebounding,[71] making production more profitable.

GREENHOUSE GASES FROM NATURAL GAS EXTRACTION

Estimating the greenhouse gas footprint of the natural gas industry is a complex process, with many data gaps. The USEPA's 2017 report *Inventory of US Greenhouse Gas Emissions and Sinks* (hereinafter *Inventory of US Greenhouse Gas*) provides some clues, including estimates of CO_2e from the production phase of oil and gas. The report estimates that 204.8 million Mt CO_2e were emitted into the atmosphere from natural gas systems in 2015.[72] These emissions are largely methane and include emissions from venting, flaring, leaking tanks and pipelines, gas engines, and other sources.[73] Sixty-six percent of these emissions occurred in the field production stage, followed by transmission and storage, which accounted for 21 percent of emissions, and processing and distribution, which produced roughly seven percent of total emissions.[74]

Applying the 1.8 percent attribution factor, 3.69 million Mt CO_2e can be applied to the production of plastic. However, as will be detailed in this section, this estimate likely significantly underestimates the greenhouse gas emissions from natural gas production and transportation—and therefore the climate impact of plastic as well.

Estimating the greenhouse gas footprint of the natural gas industry is a complex process, with many data gaps. In 2015, 204.8 million Mt CO_2e were emitted from natural gas systems. These emissions are largely methane and include emissions from venting, flaring, leaking tanks and pipelines, gas engines, and other sources.

In the United States, oil and gas drilling began in 1859[75] using conventional drilling, which consists of drilling a vertical well.[76] This process made oil and gas extraction relatively easy because tapping shallow producing fields allowed the product to be either pumped or brought to the surface under its own pressure.[77] Later processes introduced unconventional drilling, in which a well is drilled vertically and then horizontally for more than two miles.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Some studies have estimated the amount of methane lost from a shale gas well (barring any accidents or emergency venting) to be between 3.6 and 7.9 percent of its total production, which is much higher than conventional wells.[78] A recent study by Robert Howarth using satellite data estimates that even more methane is released from well development to delivery of gas: 12 percent of total production.[79] These varied estimates and the numerous data gaps demonstrate the challenge of assessing the greenhouse gas emissions from natural gas extraction. In the US, the extraction process is regulated at the state level, so reporting requirements for drilling companies vary significantly, if they exist at all. There are also no national reporting requirements for greenhouse gas emissions from this industry. In fact, in 2017, the USEPA removed its request to existing oil and gas operations for information about oil and gas equipment and emissions.[80] Requiring the industry to report greenhouse gases to states and/or the USEPA would help overcome this significant data gap.

Because of these data gaps, greenhouse gas emissions from the oil and gas industry can be estimated by looking instead at emissions sources, including those assessed in *Inventory of US Greenhouse Gas*.

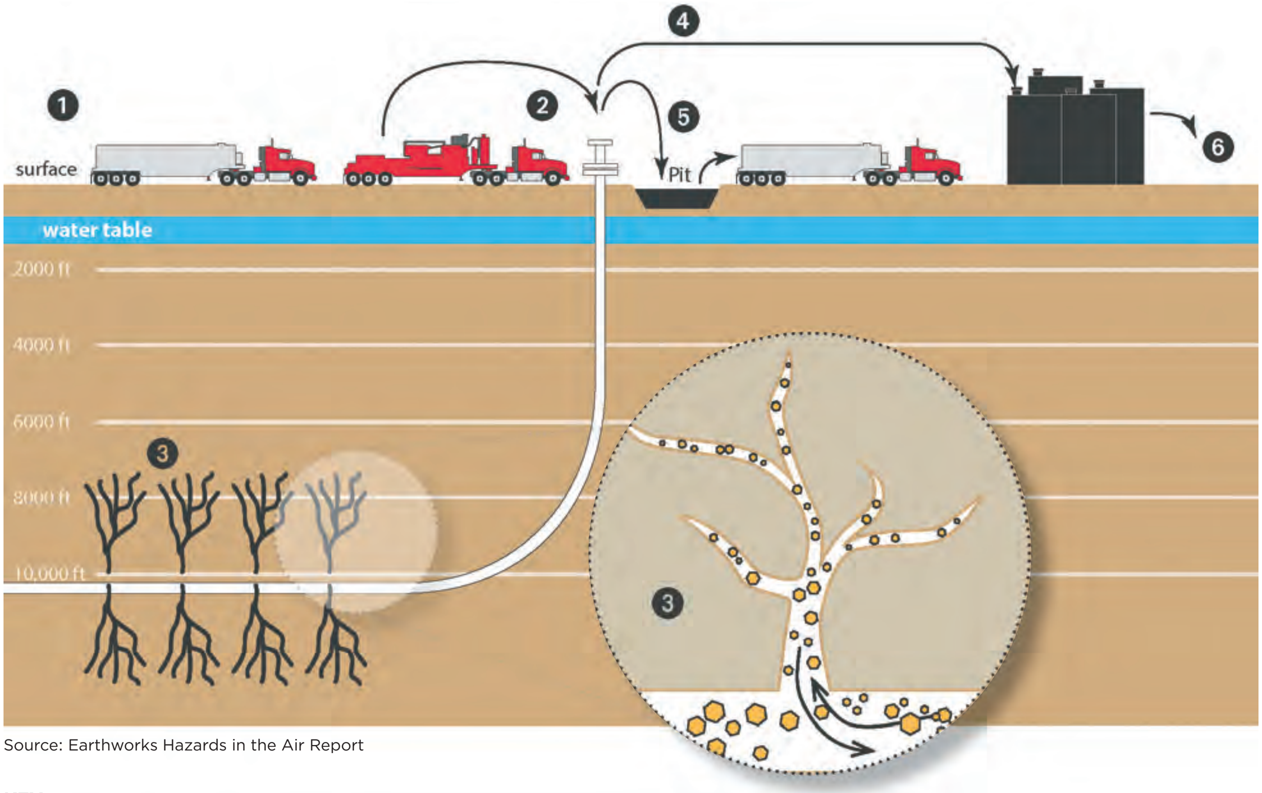
HYDRAULIC FRACTURING

The advent of new hydraulic fracturing (fracking) technologies at the turn of the 21st century enabled access to natural gas reserves that were previously unavailable for exploitation. Together, unconventional drilling and hydraulic fracturing have led to a massive oil and gas boom in recent years, which has, in turn, fueled a plastic production boom.[81]

Fracking is a pressurized process in which underground rock formations (shale) are cracked, or fracked, to release trapped oil and gas. Drilling a natural gas well today involves two key steps: directional drilling (drilling vertically into the ground, then turning the well 90 degrees to access certain hydrocarbon-containing formations) and then stimulating the formation using a mixture of chemicals, sand, and fresh water to prop open cracked shale rock. This causes oil and gas to flow out of the drilled well. One study of five unconventional wells from 2011 estimated between 0.6 and 3.2 percent methane was emitted as a proportion of lifetime production. These estimates do not include accidents or emergency venting.[82]

FIGURE 7

Unconventional Oil and Gas Production



Source: Earthworks Hazards in the Air Report

KEY

❶ Water, sand, and chemicals are hauled to the well pad
❷ Well pad is prepared, drilled, and fracked
❸ Pressurized mixture causes the shale to crack, oil and gas to flow into the well
❹ Active extraction of oil, gas, and waste fluids
❺ Transmission, storage, and distribution of oil and gas
❻ Processed water, oil, and gas are hauled to treatment for use

Significant greenhouse gases can be emitted during horizontal drilling due to the extreme distances underground that wells are being drilled today. Some wells have a total bore hole length of more than 5.2 miles per well, including horizontal portions that exceed 3.7 miles. The record for longest total well is broken every year.[83]

In 2010, the oil and gas industry drilled a cumulative distance of 45,312 miles of vertical and lateral well bores.[84] Drill site operators use a variety of heavy equipment, running either on diesel, natural gas, or electricity. One of the key pieces of equipment is the drilling rig, which comes in various sizes. Rigs capable of drilling very long laterals in a deep formation are enormous and involve multiple heavy machines.[85] Despite significant fuel consumption and attendant emissions from its operation, much of this equipment is not covered by air emissions regulations and accordingly its precise emissions, while likely significant, are not publicly reported.[86]

Fracking involves injecting water and chemicals into the well bore at very high pressures, to fracture the shale or other tight formation rock, along with proppants (usually sand) to keep those fissures open, allowing the hydrocarbons to escape. The process has been in use for more than 60 years, and it is now used in the majority of wells in the United States. In shale and other tight formations, the fluid volumes injected into the well for hydraulic fracturing are orders of magnitude above what are used in conventional oil and gas drilling operations. According to FracFocus, an industry registry site, in 2015, wells were reported to average nearly 5.5 million gallons of water injected per tap, a figure that increased to over 9.5 million gallons in 2017.[87] Many conventional wells are stimulated with much less hydraulic fracturing fluid, between 10,000 and 300,000 gallons.[88]

These water volumes impact greenhouse gas emissions for a number of reasons. Not only must the water be sourced and transported to the site (as discussed below), but the engines used to pressurize and inject the fluids and proppants also emit greenhouse gases. The hydraulic fracturing stage of the operation often requires dozens of frac pumps,[89] each of which may run on 2,500-horsepower engines.[90] Additional on-site equipment must mix the hydraulic fracturing chemicals.

> Some states are moving away from open-air impoundments to more tightly controlled storage containers, which could reduce greenhouse gas emissions from this component of the oil and gas drilling process or transfer the burden to storage tanks.

Lacking specific details on the amount and type of fuel used to operate this machinery industry-wide, the present report relies on the assumption that the petroleum and natural gas sections of USEPA's *Inventory of US Greenhouse Gas* report adequately account for these greenhouse gas emissions. As noted above, however, the lack of emissions certifications for key pieces of heavy equipment make it more likely than not that emissions from fracking operations are underestimated.

BOX 5

Storage and Transmission Systems

The natural gas system in the United States includes hundreds of thousands of wells, hundreds of processing facilities, and over a million miles of transmission and distribution pipelines. According to US Central Intelligence Agency data, in 2013 the United States had more miles of pipelines than any other country, with 1,232,999 miles in natural gas transport and 149,570 miles in petroleum products. The next closest countries were Russia (101,825 miles) and Canada (62,137 miles).[91] Pipeline data from the Pipeline and Hazardous Materials Safety Administration notes more than 2.5 million miles of distribution and transmission pipelines for natural gas, and the associated number of known compressor station facilities exceeds 10,000, significantly more than the "hundreds" cited in the *Inventory of US Greenhouse Gas* report.[92] It is therefore likely that the greenhouse gas emissions of natural gas storage and transmission systems are significantly under-calculated for 2015. The USEPA should re-examine these figures in subsequent reports.

When wastewater is temporarily stored in open impoundments on site, these ponds emit a number of volatile organic compounds, including methane. There is insufficient data to adequately estimate the total volume of liquids in these impoundments that off-gas into the atmosphere, and thus it is impossible to measure the impoundments' greenhouse gas contributions. Some states are moving away from open-air impoundments to more tightly controlled storage containers, which could reduce greenhouse gas emissions from this component of the oil and gas drilling process or transfer the burden to storage tanks. These large wastewater volumes must be transported off site for waste disposal after hydraulic fracturing is completed and gas production begins.

Venting and Flaring

As more fluid is injected for well stimulation, greater volumes of flowback return to the surface. Not all of the hydrocarbons produced by oil and gas operators enter the production stream. For a variety of reasons, including natural gas production that exceeds the capacity of pipelines and fractionators in predominately oil-producing regions and the periodic spikes in pressure in the fracking process, large quantities of gas are routinely emitted into the atmosphere (venting) or intentionally burned (flaring).[93] According to the Energy Information Administration (EIA), 289.5 billion cubic feet of natural gas, about 0.9 percent of total gas produced,[94] was vented or flared in 2015.[95]

Given that 53 Kg CO$_2$ are released from the combustion of one million British thermal units of natural gas, flaring this volume of natural gas would release 15.9 million Mt CO$_2$ into the atmosphere. This figure excludes venting, when natural gas is emitted but not combusted. In USEPA's *Inventory of US Greenhouse Gas* report, associated gas venting and flaring is listed at 3.7 million Mt CO$_2$e for petroleum systems. However, the report includes flaring from all onshore oil and gas production in the natural gas systems section,[96] where figures for flaring at the wellhead are not delineated from the broader category of field production emissions from the natural gas systems. Because of this, and because the percentage of gas vented instead of flared does not appear in the EIA flaring data, it is not possible to assess whether the USEPA's *Inventory of US Greenhouse Gas* report adequately represents the atmospheric carbon impacts of venting and flaring in 2015. More detailed data from both EIA and USEPA would be helpful for greater precision.

Raw natural gas is often not ready to be pressurized and distributed directly into the pipeline network. Prior to that process, and dependent on the formation being accessed, the raw gas must first be processed to remove other hydrocarbons (such as pentane and butane) and sulfur gases.[97]

Leaking Tanks and Pipelines

After a well is completed, it can still emit greenhouse gases both intentionally and unintentionally. Pneumatic pumps and dehydrators are the major sources of leakage, though leaks can also occur from the site's meters and vapor recovery units.[98] Storage tanks, a familiar sight on the oil and gas landscape, typically contain raw and refined liquid petroleum products and associated liquid waste products. USEPA's *Inventory of US Greenhouse Gas* estimates that emissions from natural gas systems, including pipeline emissions, were an estimated 33.7 million Mt CO_2e for transmission and storage in 2015.[99] The discussion that follows examines whether and to what extent these emissions estimates are complete.

Pipeline and Hazardous Materials Safety Administration (PHMSA) reports indicate that pipeline system leaks are rather commonplace, with 585 known leaks in transmission line systems and 25 leaks in gathering line systems awaiting repair in March 2019.[100] Volumes of escaped gases are not tracked in this context, however, so the CO_2e of these leaks cannot be calculated. Some studies have looked into pipeline emissions, but the estimates vary substantially. Globally, a review of previous research suggested that 2.5 to ten percent of the total amount of methane pumped through pipelines leaks out of the system.[101] The upper level is due in large part to leaking infrastructure in Russia, but significant leakage rates have been documented in other countries. In the United Kingdom, soil gas measurements of methane from high-pressure gas pipelines indicated a total flux of 62,600 Mt per year, or 2.9 percent of the country's total annual methane emissions.[102] In the US, a direct monitoring study on Texas pipeline emissions indicated leakage rates between 2.3 and 4.9 percent.[103] If this figure is applied to the 28.8 trillion cubic feet of marked gas in the US in 2015, the amount of gas leaked would be between 661.8 billion cubic feet and 1.4 trillion cubic feet of methane released in pipeline leaks, or between 36 and 77 million Mt CO_2e.[104] The proportion of this attributable to plastic would be between 648,000 Mt and 1.4 million Mt. The industry should make additional research into the quantity of gas released in pipeline leaks a priority.

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TRANSPORT

The considerable use of trucks to service well sites is another source of greenhouse gases in oil and gas extraction. Thousands of trucks of various sizes and capacities emit greenhouse gases to both haul water and dispose of waste.

Water Hauling

If temporary water pipelines are not constructed, water hauling is a major source of truck traffic. Average water use per injection for new wells in 2015 was approximately 5.5 million gallons.[105]

Due to the varied sizes of water hauling trucks, estimates of the number of trucks required for high-volume hydraulic fracturing operations vary significantly. One source estimates 320 trucks would be required to supply two million gallons of water, with up to 1,440 trucks needed for nine million gallons. This works out to 6,250 gallons per truck, meaning that 5.5 million gallons for stimulating one well for one injection would require 846 trips.[106]

While 6,250-gallon tankers exist, 4,000-gallon water haulers are more typical.[107] Using 4,000-gallon tankers would require 1,375 trips for a 5.5-million-gallon fracking operation. These trip calculations assume each truck must make a round trip from its water source.

Waste Disposal

Waste disposal, too, varies tremendously depending on the target formation and the amount of fluid injected into a well. A 2016 analysis from Duke University calculated 449,000-3.8 million gallons of liquid waste flowback during the life of a well in various shale plays around the United States.[108] That would require an additional 112-950 truck trips to dispose of the brine and flowback fluid. There are also a number of other waste streams to consider, including drill cuttings and drilling mud, spent lubricants and chemical containers, and earth that has been contaminated on site.[109]

Other Traffic

Trucks carrying chemicals, proppant, and equipment must also be taken to and from the site.[110] Workers, contractors, and inspectors must access the well site on a regular basis, as well. One estimate from 2011 puts the total number of truck trips accessing a horizontal well site at 3,950 heavy-duty trucks and 2,840 light trucks, totaling 6,790 trips per injection.[111] Since 2011, extraction techniques have become substantially more intensive, meaning that more recent wells require transporting even more chemicals, equipment, water, and waste.

Calculating the greenhouse gas emissions of all this traffic conclusively is difficult due to variability. However, using estimates of the CO_2 emissions of heavy-duty trucks based on Mt-miles—the product of Mt hauled multiplied by miles driven—multiplied by average freight emissions at 161.8 grams CO_2 provides a ballpark estimate. Dividing by 1,000 yields results in kilograms.

Light-duty trucks are calculated based on average fuel efficiency. For this analysis, the Ford F-250 will represent an average between vehicles used by workers to access rugged well sites, as well as the delivery of smaller items to the site that would not require heavy-duty delivery. Real-world analysis of the 2015 model of Ford F-250s average 13.7 miles per gallon. While some of these lighter-duty vehicles would likely use diesel, which emits 10,180 grams of CO_2 per gallon, this report makes the calculation with gasoline (8,887 grams) for a more conservative estimate.

Given the rapid and continuing growth of the fracking boom and associated transport activity, the 2011 estimate of 3,950 heavy-duty trucks and 2,840 light trucks does not reflect the dramatic increase in water, waste, sand, and chemicals associated with unconventional drilling in more recent years. Accordingly, any estimate based on these figures will almost certainly understate the current scale of transport-related emissions. In the absence of more current figures, however, this report incorporates the 2011 numbers to calculate a very conservative baseline.

The total emissions from trucks servicing a single unconventional well in Pennsylvania is estimated between 708–3,728 Mt CO_2, depending on the average round-trip distance. One fundamental variable to calculate the emissions related to truck traffic is the number of unconventional wells drilled in a given year. In the early days of fracking the Marcellus Shale formation, the growth rate in wells drilled per year was exponential. However, as of publication, this peaked in 2011 with 1,958 wells, before falling to barely one quarter that figure in 2016.[112]

The cumulative CO_2 emissions from trucks servicing unconventional oil and gas wells in Pennsylvania are therefore likely to be between 8.1-40.5 million Mt, depending on the distances driven. In 2015, the CO_2e emissions are between 555,000-2,774,000 Mt. It is worth noting that the 4.8 trillion cubic feet produced in Pennsylvania in 2015 represented 16.7 percent of the natural gas in the United States that year. If the state is representative of truck traffic in other regions, then the national figure of CO_2 emitted in 2015 by servicing trucks would have been between 3.2–16.4 million Mt, a figure not accounted for in *Inventory of US Greenhouse Gas.* Between 57,000–295,000 Mt CO_2e of these emissions would be attributable to plastic.

The considerable use of trucks to service well sites is another source of greenhouse gases in oil and gas extraction. Thousands of trucks of various sizes and capacities emit greenhouse gases to both haul water and dispose of waste.

PIPELINE CONSTRUCTION AND COMPRESSOR STATIONS

Pipeline construction is an intensive process. US federal pipeline safety regulator PHMSA estimates that there are more than 2.5 million miles of natural gas pipelines (excluding gathering lines) and more than 68,000 additional miles of natural gas liquid pipelines in the United States. In addition to their construction, pipelines require significant infrastructure to keep running, in particular compressor stations and metering stations.

The National Emissions Inventory, compiled by the USEPA, maintains a detailed list of emissions from point sources such as compressor and metering stations. In a significant omission, however, CO_2, methane, and other greenhouse gases are not included in the inventory for these sources, making a comprehensive evaluation of the greenhouse gas contribution of these facilities using the NEI difficult.

Replace first sentence with: Federal Energy Regulatory Commission (FERC) Environmental Impact Statements outline the potential greenhouse gas impacts of recently proposed pipeline projects.[113] For the 600-mile Atlantic Coast pipeline system stretching from North Carolina to West Virginia, an estimated one million Mt CO_2 were released during the construction phase of the project, plus an additional 973,865 Mt per year between seven associated compressor stations and 248,145 Mt from seven metering stations. In comparison, FERC documents suggest the that construction emissions for the Sabal Trail project, spanning 515 miles from Alabama to Florida, will be 200,215 Mt CO_2e. Operating emissions, blowdowns, and leaks are expected to contribute 31,104 Mt CO_2e annually. Five compressors are associated with the project, contributing 858,030 Mt per year, along with one metering station, adding 7,985 Mt.[114] The 303-mile Mountain Valley Pipeline, running from Virginia to West Virginia, is expected to generate 877,620 Mt of greenhouse gas emissions during construction, followed by 673,621 Mt annually from three compressors. Assuming these compressors are representative, these measurements suggest an average of 167,034 Mt CO_2e per year per compressor station.[115]

Annual emissions from natural gas compressor stations in the United States are almost certainly greater than 256 million Mt CO_2e, 4.6 million of which are applicable to plastic production.

Between the three projects, there are over two million Mt of greenhouse gas emissions from the construction of 1,418 miles of pipelines, along with 2.5 million Mt from 15 compressor stations and 2.856 million Mt from eight metering stations. One of the three includes an annual figure of 31,104 Mt from various sources. The average per-mile contribution annually includes 1,469 Mt for construction, 1,767 Mt from associated compressors, 181 Mt from metering stations, and 22 Mt from operation, leaks, and blowdowns. Based on this data, a compressor station is needed every 95 miles on average, and a metering station is required every 177 miles.[116]

Pipeline construction is booming, a trend that is expected to continue as more midstream infrastructure comes online. According to data from PHMSA, an average of 14,127 miles of pipeline were installed between 2000 and 2009, compared to 35,436 miles per year in the current decade.[117] Using the figures above as a guide, this calculates to over 52 million Mt CO_2e for pipeline construction per year in the current decade, in addition to bringing 362 compressors (over 60 million Mt annually) and 200 metering stations (over six million Mt annually) online every year. Collectively, this amounts to over 118 million Mt CO_2e emitted per year, of which 2.1 million Mt are attributable to plastic.

The 2014 version of the NEI includes emissions data for 1,532 compressor stations across the United States.[118] If the data from the new compressors are representative, this would indicate a baseline of nearly 256 million Mt CO_2e per year. This is similar to the 1,367 compressor stations in a dataset published by the US Department of Homeland Security (DHS). However, both of these are likely missing large numbers of compressor stations associated with gathering lines. The Oil & Gas Threat Map, a project of Earthworks, Clean Air Task Force, and FracTracker Alliance, identified 10,472 compressor stations, clustered in oil-and-gas-producing regions. These stations do not overlap significantly with the compressors reported by DHS, which are spread throughout long distribution pipeline networks. The Oil & Gas Threat Map compressor dataset is also likely to be incomplete, as 6,486 of the facilities (62 percent) are in the state of Louisiana alone. While Louisiana is a major oil-and-gas-producing area, it is not the biggest, and compressors in other states are likely to be significantly underrepresented.

The NEI data has some overlap with the Oil & Gas Threat Map and DHS maps. While it is incomplete in scope, the NEI data has some dense clusters of gathering line compressors in geographies not covered by the Oil & Gas Threat Map, notably in Kansas and southern Appalachia. The lack of a comprehensive dataset of compressor stations in the United States is a significant data gap for understanding the aggregate greenhouse gas emissions from this segment of the supply chain for natural gas and, accordingly, for plastic.

Applying the average calculated above to the compressor stations included in the NEI dataset results in annual emissions of 256 million Mt CO_2e, with 4.6 million Mt attributable to plastic. This figure, however, fails to consider the majority of compressor stations as indicated in the Oil & Gas Threat Map. Those stations in the Oil & Gas Threat Map likely have smaller per-station emissions, and the emissions average calculated above cannot reliably be applied to those stations. As such, annual emissions from natural gas compressor stations in the United States are almost certainly greater than 256 million Mt CO_2e, 4.6 million of which are applicable to plastic production.

Land Disturbance

Oil and gas extraction, pipelines, and processing facilities inherently require intensive use of the landscape. This is especially true for modern, industrial-scale unconventional drilling operations. This land disturbance impacts the industry's greenhouse gas footprint.

Based on analysis conducted in 2010 and 2011 with respect to fracking operations in Pennsylvania, the Nature Conservancy estimated that while a Marcellus Shale well pad might only measure three acres on average, it also requires an additional 25 acres of land disturbance for related infrastructure, or 28 acres including gathering lines to take the gas to processing facilities, the construction of access roads, water impoundments, and related infrastructure.[119] Gathering pipelines require the greatest proportion of ground clearing, averaging 19 acres per site, assuming the gathering lines average 3.1 miles in length and include a 50-foot right of way.

Assessing the total impact of land-clearing activities related to oil and gas extraction is impeded by lack of clarity around which oil and gas wells are on multi-acre pads and how many are conventional operations, which may involve a cleared area of a quarter acre or less, not counting gathering line routes. There are now some well pads with 30 or more wells, although this is relatively rare, and the pad size in those cases are closer to ten acres than the three acres calculated by the Nature Conservancy.[120]

A recent report looked at the land footprint of natural gas extraction from more than a half million producing gas wells in 2015, reasoning that the average between conventional and unconventional well pad construction would be five wells on a five-acre site, or an acre per well.[121] This figure did not include gathering lines. If the Nature Conservancy's estimate of clearing 19 acres of gathering line per well site can be extrapolated across the United States, gathering lines would account for 2,110,383 acres of cleared land connecting 111,073 drilling sites, and the combined gathering line and well pad area would include 2,665,747 acres of cleared land.

These calculations are subject to a number of assumptions, and a comprehensive study on the footprint of oil and gas extraction and transmission operations would increase confidence in these findings substantially.

The estimated 28 total acres of land disturbance for unconventional oil and gas well pads, including the associated gathering lines, is only a small portion of the overall land disturbed. Distribution pipelines are the single largest cause of ground


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disturbance in oil and gas extraction processes. PHMSA estimates there are 2.7 million miles of gas- and petroleum-related pipelines in the United States, not counting gathering lines.[122] The width of a typical pipeline right of way is 50–100 feet, and 50 feet is more common for a permanent easement.[123] At that width, a pipeline would disturb 6.06 acres per linear mile,[124] meaning the aggregate disturbance would be 16.6 million acres, an area slightly larger than the combined size of West Virginia and Rhode Island.[125]

The greenhouse gas contribution of that cleared land can be considerable, depending on the vegetation profile of the land in question. The focus here will be on forested land, which represents about 33 percent of land cover in the US.[126] The average forested land in the United States contains 158,000 pounds of organic carbon per acre,[127] which when disturbed will mostly be released into the atmosphere as 263 Mt CO_2 per acre.[128] In addition to this one-time release of carbon, most of this land would need to remain free from tree growth for the duration of the pipeline's existence, and would therefore cease absorbing carbon[129] from the atmosphere on a continuing basis. In 2015, US forests removed 778.7 million Mt CO_2e[130] from an inventory of 766 million forested acres,[131] or about 1.02 Mt CO_2e removal per acre per year.

In total, approximately 19.2 million acres of land have been cleared for oil and gas development in the United States. Assuming that a third of this land impacted is forested, this amounts to a one-time release of 1.686 billion Mt CO_2 into the atmosphere, along with the removal of 6.5 million Mt of carbon sink capacity on an annual basis. Recognizing that this land disturbance reflects a wide array of oil and gas development and distribution infrastructure developed over the course of many decades, it is neither feasible nor appropriate to apportion the emissions from historic land disturbance to recent or ongoing plastic production. It is nonetheless important to acknowledge the scale of emissions from a source that receives little attention. New pipelines associated with natural gas production are actively being constructed or proposed, and still more expansions are projected in the years to come. As discussed more fully later, these pipelines are increasingly driven not only by demand for natural gas in energy production, but by the rapid expansion of infrastructure for the production and export of plastic, plastic resins, and plastic feedstocks.

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As mentioned above, PHMSA data indicate an average of 6,194 miles of pipelines built per year in the current decade, resulting in an estimated 37,573 new acres cleared, of which 12,512 were likely forested. This means the eventual release of 3.3 million Mt CO_2 into the atmosphere from land-disturbing activities in 2015, plus the permanent loss of forest carbon sinks capable of absorbing 13,000 Mt CO_2 per year. With respect to plastic, this would yield an estimated contribution of 59,461 Mt of new carbon in 2015 and a failure to remove existing carbon due to land clearing associated with oil and gas development.

NATURAL GAS STORAGE AND DISPOSAL

Natural gas storage (temporary) and waste disposal sites (permanent) are two often overlooked areas in accounting for the oil and gas industry's emissions footprint. Accidents, leaks, and unplanned releases are difficult to quantify but still significant sources of emissions for the industry. The high-profile example of Aliso Canyon can serve as a case study.

In October 2015, a gas leak was noticed in one of 115 wells servicing Aliso Canyon,[132] an enormous gas storage facility in the Los Angeles, California, area. By the following February, when the leak was finally sealed, an estimated 90,300–108,950 Mt of methane had been released into the atmosphere.[133] This range corresponds to 2.53–3.05 million Mt CO_2e. This single emissions event released more than one percent of the total emissions from natural gas systems reported by the USEPA in 2015.

The Aliso Canyon accident was the largest natural gas leak in US history. While this release was unique in its scale, releases of this kind happen with alarming frequency across the oil, gas, and petrochemical industries. Additional high-profile accidents, including those in Crosby and Deer Park, Texas,[134] are drawing attention to sudden, accidental, and unaccounted for releases of greenhouse gases that exceed permissible amounts of emissions under the permits filed with regulators and further distort the total amount of emissions released in petrochemical processes. Smaller accidents, leaks, and unplanned releases remain harder still to document and quantify.

GAS PROCESSING

Natural gas and crude oil are rarely useable without some degree of processing. Natural gas is processed and separated into methane gas and natural gas liquids like ethane, propane, butane, condensate, and gasoline at natural gas plants and fractionators. Oil is processed into products such as gasoline, jet fuel, lubricants, and naphtha at petroleum refineries. This section focuses on emissions from natural gas processing plants.

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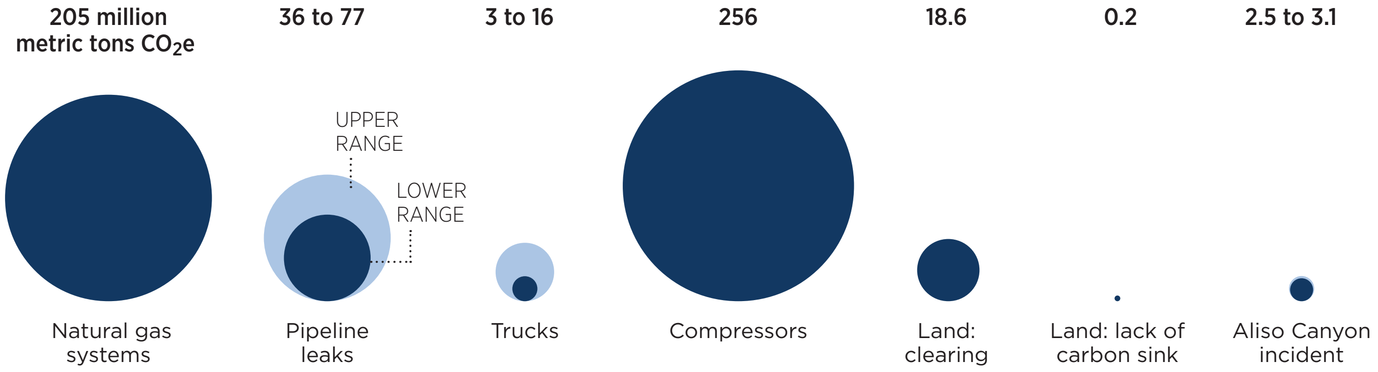
The USEPA requires gas processing plants to measure and report greenhouse gas emissions if they process at least 25 MMcf of gas per day. In 2015, 467 gas processing plants reported releasing 59 million Mt CO_2e (roughly 55 million Mt CO_2 and 4.08 million Mt methane as CO_2e). A large share of these emissions were from fossil fuel combustion, while the rest were from processes that include acid gas removal units, other flare stacks, compressors, blowdown vent stacks, dehydrators, and equipment leaks.[135]

One industry analysis reviewed emissions intensity—the amount of CO_2e released for each MMcf of gas processed—at ten plants based on natural gas throughput and greenhouse gas emissions from 2012. Emissions rates ranged from 0.616-3.387 Mt CO_2e per MMcf processed, with an average of 1.668 Mt per MMcf and a median of 1.546 Mt per MMcf. Emissions intensities based on NGL production ranged between roughly 0.01 to just over 0.07 Mt per gallon.[136]

Facilities that start up, shut down, or malfunction unexpectedly may emit more greenhouse gases than a plant that is operating safely and efficiently. For instance, in 2014, DCP Midstream's Goldsmith gas plant in Ector County, Texas, reported processing an average of 60 MMcf of gas and releasing 239 million Mt CO_2e, meaning that it released 10.9 Mt CO_2e per MMcf of gas processed.[137] That year, the plant also reported unauthorized emissions from one startup event, two maintenance events, and 99 other emissions events to the Texas Commission on Environmental Quality.[138] These unplanned emissions events suggest operational problems at the plant, and they often result in higher emissions due to leaks and/or increases in venting and flaring. Preventing and avoiding unplanned emissions events can reduce greenhouse gas emissions and emissions of other

FIGURE 8

Emissions Associated with Petroleum Extraction



Source: Calculations by FracTracker Alliance.

dangerous pollutants, but in the absence of better controls, these incidents provide an additional and unpredictable source of greenhouse gas impacts from the plastic lifecycle.

CASE STUDY: PENNSYLVANIA

As noted throughout this chapter, sources of detailed and reliable emissions data are lacking at the national and global level for many important links in the supply chain for oil, gas, natural gas liquids, and plastic. Because the oil and gas industry is regulated state by state, much of this data is published at the state level. For some producing states, regulations and emissions data are as or more limited than data from federal sources. Pennsylvania releases more comprehensive oil and gas data than most and therefore serves as a good example for understanding the industry's carbon impacts.[139] Accordingly, this data can shed additional light on the nature and scale of potential emissions from this sector.

Wells and Production

According to EIA, Pennsylvania produced 4.81 trillion cubic feet of natural gas in 2015, ranking second only to Texas in total quantity of gas.[140] Pennsylvania also ranked second to Texas in the number of producing gas wells that year, with 70,051 wells.[141] Records from the Pennsylvania Department of Environmental Protection are different, although in the same ballpark. Total gas production for the year is listed at 4.77 trillion cubic feet from 79,216 producing wells.

From the numbers, it is clear that the vast majority of production comes from a limited number of unconventional wells. Accounting for just nine percent of the state's producing well inventory, unconventional wells produce over 96 percent of Pennsylvania's natural gas.[142] The average unconventional well produced 277 times the amount of gas as its conventional counterpart in 2015.[143] As a result, it is safe to extrapolate that unconventional drilling from formations such as the Marcellus Shale is the largest contributor to Pennsylvania's gas extraction industry.

Water, Proppant, and Chemical Usage

Unconventional well operators in Pennsylvania are required to submit information to the national registry known as FracFocus about the quantity of materials injected into the well bore during the hydraulic fracturing stage of operations.[144] Reports have been submitted for 932 wells in Pennsylvania in 2015,[145] in which fracking operations used a total of 8.5 billion gallons of water, averaging about 9.15 million gallons of water per well. An unknown quantity of the water may have been piped into the well pads, but if it were all trucked to the well site, it would have required 2,132,051 water haulers with a 4,000-gallon capacity.

The same source also reports on the ingredient mass (excluding water) injected into the well.[146] The most common ingredient is fine sand (e.g. frac sand) mined in the upper Midwest, which props open the shale fractures. Other ingredients include chemicals that are designed to increase production and eliminate problems in the well bore. These arrive via intermodal routes that may include trucks, rail, and river barges, with trucks required to bring the material the final distance to the well site. Pennsylvania wells completed in 2015 used nearly 28.5 million Mt of these materials,[147] which would require 994,415 trucks hauling loads of 28.75 Mt of material. Some wells reported the use of water but no amount of sand or chemicals.[148]

Waste

According to the self-reported data that oil and gas operators submitted to the Pennsylvania Department of Environmental Protection, 49,397,351 barrels (2.1 billion gallons) of liquid waste were produced from oil and gas wells in the state in 2015, along with 1,117,351 tons of solid waste.[149] Hauling that waste would require nearly 519,000 full, 4,000-gallon liquid waste haulers.[150] For solid waste, the amount of waste that can be carried depends significantly on local roads, as some roads and overpasses have weight restrictions that are more stringent than Pennsylvania's statewide gross weight limit of 40 tons.[151] The weight of a large, empty dump truck is variable, but weights ranging from 11.25–13.5 tons are common.[152] This makes 28.75 tons an extremely heavy load, and the solid waste generated in Pennsylvania in 2015 would require a minimum of 38,865 trucks of this capacity.[153]

According to the self-reported data that oil and gas operators submitted to the Pennsylvania Department of Environmental Protection, 49,397,351 barrels (2.1 billion gallons) of liquid waste were produced from oil and gas wells in the state in 2015, along with 1,117,351 tons of solid waste.

TABLE 2

Pennsylvania Production Figures, 2015

Category	Conventional	Unconventional	All Wells
Production (Mcf)	169,695,753	4,600,905,454	4,770,601,207
Well Count	72,147	7,069	79,216
Average Production (Mcf/Well)	2,352	650,857	2,142

Source: Pennsylvania Department of Environmental Protection.

TABLE 3

Ingredients Injected into Pennsylvania Gas Wells by Mass and Volume

Item	Ingredient Mass (pounds)	Water Volume (gallons)
Sum of Values	57,178,881,364	8,528,204,586
Count of Wells	630	932
Average Values per Well	90,760,129	9,150,434

Source: Pennsylvania Department of Environmental Protection.

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The principal source of greenhouse gases for injection wells is traffic to and from the site. A paper by Chesapeake Energy discussed the idea of treating and reusing deep formation brines produced in Pennsylvania in other oil and gas wells, indicating that the process would save 52,500 road miles of transportation of waste to distant injection wells per production well drilled. According to their calculations, this would save 88 Mt CO_2 emissions per well.[154] Using, as a point of comparison, Duke University's high-end figure of 3.8 million gallons of flowback per unconventional well and using 4,000-gallon trucks generates an estimate of 950 trucks travelling an average round trip of 55 miles, the truck mileage estimates presented in the present report are reasonable.

Land Use

Using the figure of 28 acres of impact per well pad, including access roads, impoundments, gathering lines, and staging areas, Pennsylvania's unconventional wells are situated on 3,715 well pads, meaning the total disturbed area would be 104,020 acres. In addition, Pennsylvania has 91,302 miles of oil and gas pipelines according to PHMSA, excluding gathering lines, which are calculated above. With a 50-foot right of way, the disturbed area for pipelines is an additional 553,290 acres.

According to research from Pennsylvania State University, forests cover approximately 59 percent of land area in Pennsylvania.[155] It is likely that the areas in which unconventional oil and gas are developed are at least this forested, as they avoid urban and suburban Philadelphia, most of the urban and suburban Pittsburgh region, and significant portions of farmland in the south-central part of the state. Therefore, it is reasonable to assume that about 387,813 of the 657,310 acres impacted by unconventional oil and gas and pipelines in the state were originally forested.

This works against the natural role of the forest as a carbon sink. Nationally, forests store about 14 percent of all carbon emissions, and forested land in the US stores an average of 71.7 Mt of organic carbon per acre, so this is an important function. This would mean a disruption of 27.8 million Mt of organic carbon in Pennsylvania's forests. Forests in the state absorb an average of 528 kg of carbon per acre per year, meaning that the carbon sink in the state has been reduced by a total capacity of 451,414 Mt per year.

Projected Buildout

Public statements by industry and governmental sources alike project continued buildout in the Marcellus shale region over the next three decades. The EIA projects that Appalachian natural gas production will see an increase of more than 350 percent from 2013 to 2040. Specifically, NGL production is projected to increase over 700 percent by 2023 compared to 2013 figures.[156]

In line with those projections, the CNA Corporation forecasts 47,600 additional wells drilled from 2015 to 2045, in the Marcellus Shale formation in Pennsylvania.[157] Cumulatively, this buildout would require 583 billion gallons of fresh water and 386 million tons of sand, based on a 2018 analysis of 2017 data.[158] According to a 2011 estimate of 6,790 truck trips per well, the cumulative requirement would exceed 323 million truck trips.[159] These wells would produce an estimated 1.7 billion gallons of liquid waste and 588,000 tons of solid waste. Between existing, proposed, and projected well pads and pipelines, the total area impacted by oil and gas extraction and midstream operations would approach 800,000 acres.

Reducing Emissions

Some USEPA estimates project that up to 90 percent of methane emissions could be reduced

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per unconventional well using technologies associated with reduced emissions (reduced emissions technologies, or RECs), also known as “reduced flaring completions” or “green completions.”[160] RECs include sand traps, separators, portable compressors, membrane acid gas removal units, and desiccant dehydrators. For wells that require fracking, RECs may be a viable way to recover natural gas and condensate during well completion, since operators can offset the costs by selling the captured gas. However, RECs cannot be conducted without access to pipelines prior to well completion, which is not always possible for exploratory wells or in newly developed extraction areas.[161] If pipelines are not available to direct the processed gases, flare tanks can be used to combust the waste gases and can be transported from site to site.[162] RECs are currently required for new or modified wells, but not existing ones.

Beyond fracking bans and other measures to limit production, one of the best ways to reduce emissions from the extraction and transport of natural gas products is to detect the sources of leaks and unnecessary releases. However, in September 2018, the Trump administration proposed weakening two rules that require companies to test for and repair methane leaks, among other measures, on federal lands via a finalized rule[163] from the US Department of Interior and on private lands through a USEPA amendment.[164] Some estimates suggest that because of the USEPA’s proposed rule change, methane emissions could increase by a total of 344.73 Mt over USEPA’s baseline, between 2019 and 2025.[165] The Department of Interior’s rule change is currently being contested in court, and the public comment period for the USEPA’s amendment ended in October 2018. Considering the already detrimental greenhouse gas contributions from the industry, these rule changes will only serve to increase emissions.

> Beyond fracking bans and other measures to limit production, one of the best ways to reduce emissions from the extraction and transport of natural gas products is to detect the sources of leaks and unnecessary releases. However, in September 2018, the Trump administration proposed weakening two rules that require companies to test for and repair methane leaks.

EXTRACTION AND TRANSPORT EMISSIONS GAPS

Inventory of US Greenhouse Gas cites substantial greenhouse gas emissions from the oil and gas industry, with natural gas systems ranking second on the report for methane emissions and fourth among all categories for CO_2 emissions.

However, the lifecycle greenhouse gas impact of oil and gas development associated with the plastic industry remains inadequately documented and poorly understood. There are instances where there is little data, such as total emissions from machinery at the well site. There are also items that seem to underrepresent other known sources of data, including the total mileage of the US pipeline system and the number of compressor stations. Finally, there are impacts that are not considered at all, including truck traffic and other intermodal transportation requirements, as well as the effects of land clearing for wells, pipelines, and related infrastructure on releasing carbon into the atmosphere and hindering the forest’s ability to act as a carbon sink.

Taken together, the total greenhouse gas impact of oil and gas extraction substantially exceeds the already alarming totals in *Inventory of US Greenhouse Gas*. Meaningful reductions in greenhouse gas emissions are unlikely to happen without making significant reductions in these massive industries, which are just the first steps in plastic production.

CHAPTER FIVE

Refining and Manufacture

The majority of research estimating greenhouse gas emissions has primarily focused on indirect and direct emissions from the point of plastic manufacturing onward.[166] This includes emissions from cracking natural gas and petroleum-based feedstocks like ethane, propane, and naphtha into ethylene, propylene, and other monomers. With further processing and the addition of catalysts, the bulk of these monomers are converted into plastics like PE, PP, and PS, which are pelletized and sold as resins. Petrochemical and resin manufacturing capacity is currently expanding globally, with a wave of new or expanded capacity slated to come online between 2019 and 2023.

This chapter does not attempt to provide a firm estimate for all emissions from the production and manufacture of plastic. The diversity of processes and their emissions profiles makes such estimates extremely difficult. Rather, this section does five things. First, it explains the challenges of making such estimates and outlines the major sources of greenhouse gas emissions from the various stages of plastic production and manufacture. Second, using United States ethylene production as a case study, it tabulates current and future US emissions from this major source of emissions that is expected to increase significantly in the next several years. Third, this chapter provides current and future global estimates for emissions from the cracking process as applicable to the production of ethylene. Fourth, it compares existing cradle-to-resin lifecycle estimates for emissions intensity, noting where emissions may be undercounted. Finally, this section provides recommendations for reducing greenhouse gas emissions from plastic production and manufacture.

CHALLENGES OF CALCULATING EMISSIONS FROM REFINING AND MANUFACTURE

Emissions from the refining and manufacturing stage of the plastic lifecycle are considered industrial emissions. While overall sectoral emissions are reasonably well understood and quantified, apportioning those emissions to the refining and manufacture of plastic presents challenges.

Industrial sources accounted for 15.4 Gt of CO_2e emissions, or 32 percent of global CO_2e emissions, in 2010.[167] Industry emissions were calculated based on direct energy-related emissions, indirect emissions from electricity and heat, process CO_2 emissions, emissions of non-CO_2 greenhouse gases, and direct emissions from waste and wastewater. Manufacturing accounts for roughly 98 percent of total direct CO_2e emissions from the industrial sector, with most of these emissions arising from the chemical reactions and fossil fuel combustion needed to produce the intense heat needed for these reactions.[168] These emissions are dominated by a handful of energy-intensive, high-emitting industries, including chemicals and petrochemicals, iron and steel, cement, pulp and paper, and aluminum.[169] The chemical sector is second only to steel among industrial emissions sources, accounting for 15 percent of all direct emissions from industrial sources[170] and 1.5 Gt CO_2e emissions in 2010.[171]

As the IPCC notes, calculating emissions from the chemical sector poses significant "methodological and data collection challenges."[172] It recognizes, however, that greenhouse gas emissions from chemical production are dominated by a small number of key outputs.[173] Of the five key chemical outputs identified by IPCC, three

Opposite: © Carroll Muffett/CIEL

(ethylene, adipic acid, and caprolactam) are used primarily in the production of plastic and synthetic fibers. Ammonia and nitric acid are used principally for fertilizer production, with about five percent of ammonia also used in synthetic fibers.[174]

The myriad industrial processes and pathways from which fossil fuels become plastic, and the number of stages of such production, make specific attribution of industrial emissions of greenhouse gases to plastic production extremely difficult.

In addition to direct emissions from chemical processes, chemical manufacturing is profoundly energy intensive, and the production of plastic feedstocks and resins is the most energy-intensive sub-sector of the chemical industry. As the IPCC notes, "[s]team cracking for the production of light olefins such as ethylene and propylene is the most energy consuming process in the chemical industry."[175]

Even when only process and indirect-energy emissions are considered, calculating emissions from plastic production poses unique challenges because of the heavy integration between the production of plastic monomers and resins, and the production and combustion of the fossil fuels that provide both the primary feedstocks and energy source for plastic production. For example, a 2008 analysis of energy use in the petrochemical sector noted that basic chemicals and plastic resins accounted for 60 percent and more than 20 percent, respectively, of all energy expenditures in the chemicals industry.[176] The largest market for basic chemicals themselves is plastic production.

In the United States, for example, 70 percent of all petrochemicals become plastic resins, synthetic rubber, or manufactured fibers.[177] Indeed, as noted in a 2008 report by Lawrence Berkeley National Laboratories, emissions calculations for plastic are further complicated because the two most important of these basic chemicals, ethylene and propylene, are classified as energy products (rather than chemicals) under some, but not all, classification schemes.[178] A more recent analysis by the American Chemistry Council reported that 77 percent of all energy consumed by the chemistry sector was used in the manufacture of petrochemicals or plastic.[179]

The myriad industrial processes and pathways from which fossil fuels become plastic, and the number of stages of such production, make specific attribution of industrial emissions of greenhouse gases to plastic production extremely difficult. Despite these challenges, this chapter attempts to identify and, where possible, quantify the major sources of greenhouse gas emissions in the refining and manufacture stages of the plastic lifecycle.

EMISSIONS SOURCES

Known and quantifiable emissions from plastic production and manufacture are mostly direct, meaning they are owned or controlled by the manufacturing facilities themselves. Studies that evaluate greenhouse gas emissions from petrochemical production typically group emissions into two source categories: those from fuel combustion and those from manufacturing processes (process emissions).[180] Emissions from fuel combustion include those from burning natural gas, oil, coal, or other fuels for the purpose of providing power or heat for industrial processes. Process emissions include emissions that occur when natural gas liquids and other petrochemical feedstocks are converted into usable products, like ethylene, propylene, and plastic resins. Fuel combustion accounts for the bulk of emissions. For instance, according to the International Energy Agency, 85 percent of the global petrochemical industry's carbon dioxide emissions come from fuel combustion, while 15 percent comes from processes.[181]

Direct greenhouse gas emissions from petrochemical and resin manufacturers typically depend on facility efficiency, configuration, and age, the desired end product or product mix, preferred feedstocks, fuel sources, and regulatory constraints and compliance (such as emissions limits, requirements for emissions control technologies or practices, and enforcement). Some of these emissions are relatively straightforward to quantify, while others are more difficult or involve greater uncertainty. For instance, emissions that occur during routine operations or where permits require monitoring are usually easier to quantify, while direct emissions from accidents, malfunctions, and leaks involve more speculation.

Industrial expansions have already and will continue to release greenhouse gases during construction, modification, or expansion of manufacturing plants, as these projects can take several years to complete due to their enormous complexity, size, and cost. However, the greenhouse gas impact from this industrial buildout is also difficult to accurately quantify without policies that require robust emissions accounting and environmental impact assessments. New and expanded ethane crackers and resin manufacturing plants in the United States are not required to estimate construction emissions to obtain an air permit.

The transportation of intermediate and final products, and the associated infrastructure expansion to get those products to new markets, also result in greenhouse gas emissions.

Some indirect emissions associated with petrochemical and resin manufacturing stem from displaced land use, like deforestation or filling wetlands, which accompanies both new construction and expansion projects that are often massive in order to provide economies of scale. Other indirect emissions come from the generation and use of co-products that are not typically considered part of the plastic lifecycle, like residual fuel or coke from oil refineries that also crack naphtha into ethylene and other products. Indirect emissions can also result from downstream market changes that reinforce dependency on fossil fuels—like cheap plastic pricing other packaging materials out of the market, though these are difficult to estimate.[182]

STEAM CRACKING

Ethylene cracking, or steam cracking, is by far the largest direct source of emissions at this stage in the plastic lifecycle. Steam cracking is a multi-step, energy-intensive process. It involves sending feedstocks like ethane or naphtha through steam cracker furnaces, where it is heated to between 750°C and 1,100°C and mixed with steam to split the feedstock into smaller hydrocarbon molecules. Chemical reactions occur before the output from this step is sent to quenching and heat recovery, where products are partially condensed, and steam and pyrolysis gas are recovered. From there, products are compressed to around 3,500 kilopascals (kPa) (for comparison, a car tire requires between 196 and 234 kPa) and acid gas, CO_2, and water are removed. Next, the cracked gas is refrigerated and molecules of different weights are separated, through a process called fractionation, into salable products like ethylene, propylene, butadiene, hydrogen, and benzene and other aromatics.[183]

The first step in this process—heating and providing steam for the steam cracker furnaces—is the largest source of emissions in steam cracking because of the huge amount of energy it requires. For example, emissions from steam crackers often account for two-thirds of the greenhouse gas emissions associated with newly permitted ethylene manufacturing units in the United States. Five recently permitted cracking furnaces at a new ethylene unit at Occidental Chemical Corporation's Ingleside, Texas, plant account for 62 percent of the 474,976 tons of CO_2e per year that the facility is authorized to release under the Clean Air Act. A new, larger ethylene facility at ExxonMobil's Baytown, Texas, olefin plant runs

BOX 6

Pennsylvania Production Case Study

Recent developments in the US state of Pennsylvania provide a useful snapshot of these dynamics and the variety of emissions sources.

Ethane and natural gas liquids fracked from the Marcellus and Utica Shale formations in Pennsylvania are fueling the construction of a major new Shell ethane cracker in Beaver County, Pennsylvania, where they are cracked into ethylene to be exported for use in plastic production. The construction and operation of infrastructure required to support this new trade route has a significant environmental and climate impact.[184] Exporting ethane and propane from the Marcellus formation involved reconfiguring an idled refinery outside of Philadelphia into an export terminal for natural gas liquids (now called the Marcus Hook Industrial Complex), constructing the Mariner East pipeline(s) and associated compressor stations to carry fracked gas across Pennsylvania,[185] constructing and operating seven 180-240-meter-long "Dragon" ships that carry 800,000 Mt of ethane per year across the Atlantic Ocean,[186] and upgrading and operating two INEOS petrochemical facilities in Grangemouth, Scotland, and Rafnes, Norway, which collectively released 967,093 Mt CO_2 in 2016.

Ethylene and petrochemicals from these facilities are used as feedstocks to manufacture plastic on site and elsewhere in Europe. Sunoco, the operator of the Marcus Hook Industrial Complex and Mariner East pipeline, is currently trying to complete construction of an additional pipeline alongside the original Mariner East pipeline called Mariner East II, and has plans to add a third called Mariner East 2x.[187] This new pipeline project has already violated environmental laws, and Sunoco has been required to pay millions of dollars in civil penalties assessed by the Pennsylvania Department of Environmental Protection.[188]

eight steam cracker furnaces that account for 67 percent of the facility's 1.45 million tons authorized for its annual CO_2e emissions.[189] The emissions estimates are based on maximum annual permit limits that are set with the assumption that facilities will use the best available (and affordable) emissions-control technologies and practices to keep emissions "low."

Naphtha cracking is more energy intensive than ethane cracking, which results in more greenhouse gas emissions. It requires higher temperatures compared to ethane and propane, though the process generates more opportunities to recover steam that can be used as a heat source in other processes or recycled.

Emissions from steam cracking are generally higher when naphtha, instead of ethane, is used as a primary feedstock. Most ethylene crackers in the US and the Middle East use ethane as the primary feedstock, while those in Western Europe, Japan, and China use naphtha.[190] Naphtha cracking is more energy intensive than ethane cracking, which results in more greenhouse gas emissions. It requires higher temperatures compared to ethane and propane, though the process generates more opportunities to recover steam that can be used as a heat source in other processes or recycled.[191]

TABLE 4

Estimated Annual Global CO_2 Emissions from Steam Cracking, 2015–2030

	2015	2030
Global ethylene capacity (million Mt per year)	143.8	191.2–195.5
Feedstock mix	35% ethane, 47% naphtha, 18% other	38.5% ethane, 44% naphtha, 17.5% other
Feedstock-based emission factors (Mt CO_2/Mt ethylene)	1–1.2 (ethane) 1.6–1.8 (naphtha) 1 (other)*	
Estimated CO_2 emissions from global steam cracking (million Mt per year)	184.3–213.0	241.7–286.2
Coal-plant equivalency	45–52	59–69

Note: Baseline feedstock mix is for 2017, and future feedstock mix is estimated for 2027. Coal plant equivalency assumes a new base-load coal plant running at all times emits 4.13 million Mt of CO_2e per year.

Sources: Philip Reeder, *Analysis: Naphtha's Challenge in the Age of Petrochemical Feedstock Boom*, S&P Global Platts (Mar. 15, 2018, 2:04 AM), https://www.spglobal.com/platts/en/market-insights/latest-news/petrochemicals/031518-analysis-naphthas-challenge-in-the-age-of-petrochemical-feedstock-boom; Oil & Gas Journal, Special Report: International Survey of Ethylene from Steam Crackers (2015), https://www.ogj.com/content/dam/ogj/print-articles/volume-113/jul-6/International-survey-of-ethylene-from-steam-crackers--2015.pdf; Tao Ren et al., *Olefins from Conventional and Heavy Feedstocks: Energy Use in Steam Cracking and Alternative Processes*, 31 Energy 425 (2006), https://www.researchgate.net/publication/222578401_Olefins_from_conventional_and_heavy_feedstocks_Energy_use_in_steam_cracking_and_alternative_processes.

According to one estimate, ethane cracking generates 1-1.2 Mt CO_2 per Mt ethylene produced, while naphtha cracking generates 1.8-2 Mt CO_2 per Mt ethylene or 1.6–1.8 Mt CO_2 per Mt high-value chemicals (other than ethylene).[192] This suggests that naphtha cracking generates 73 percent more CO_2 per Mt of ethylene than ethane cracking.[193]

In 2017, 47 percent of the world's ethylene was manufactured using naphtha, 35 percent from ethane, and 17 percent from other feedstocks.[194] This mix is expected to shift by 2027 to 44 percent naphtha and 38.5 percent ethane.[195] Total global ethylene production capacity was 143.7 million Mt in 2015.[196] Capacity is expected to increase by 33-36 percent by 2030, to between 191 million Mt and 195 million Mt per year. Potential CO_2 emissions are between 241.7 and 286.2 million Mt per year by 2030, a growth of up to 34 percent in 15 years.

CASE STUDY: GREENHOUSE GAS EMISSIONS FROM US ETHYLENE PRODUCTION AND PROJECTED EXPANSIONS

In 2015, 28 industrial facilities in the US were home to ethylene crackers, according to Oil and Gas Journal's International Survey of Ethylene from Steam Crackers. These facilities were capable of producing 28.4 million Mt of ethylene per year. Six of the 28 primarily used naphtha as a feedstock, accounting for about 20 percent of capacity.[197] The remainder relied on mixtures of ethane, propane, and butane, with one facility relying on 100 percent refinery gas.

These industrial facilities reported emitting a total of 53 million Mt CO_2e in 2015 to the USEPA's Greenhouse Gas Reporting Program.[198] Only 24 of the 28 facilities reported enough information to determine the portion of emissions that could be attributed to ethylene production: 17.5 million Mt CO_2e per year, or one third of their total reported emissions. Emission rates varied between 0.03 to 1.88 Mt CO_2e per Mt of ethylene capacity, with an average of 0.74 Mt CO_2e per Mt of ethylene capacity.

US ethylene capacity is expected to grow rapidly over the next several years. Twelve cracker projects

TABLE 5

Greenhouse Gas Emissions from US Ethylene Producers

Plant (location)	2015 Capacity (Mt per year)	Feedstock Mix	Total CO_2e Emissions Reported (Mt)	% from Ethane Cracking	Emissions Rate (CO_2e from ethylene/ ethylene capacity)
BASF Fina Petrochemicals (Port Arthur, TX)	860,000	Naphtha (100%)	1,659,452	97%	1.88
Chevron Phillips Chemical (Cedar Bayou, TX)	835,000	Ethane (30%), Propane (20%), Butane (25%), Naphtha (25%)	1,031,152	90%	1.1
Chevron Phillips Chemical (Port Arthur, TX)	855,000	Ethane (80%), Propane (15%), Butane (5%)	784,276	72%	0.66
Chevron Phillips Chemical (Sweeny, TX)	1,950,113	Not reported	1,411,258	96%	0.69
Dow Chemical (Freeport, TX)	1,640,000	LHC 7: Ethane (50%), Propane (50%) LHC 8: Ethane (10%), Propane (20%), Naphtha (70%)	2,656,304	N/A	N/A
Dow Chemical (Plaquemine, LA)	1,260,000	LHC 2: Ethane (75%), Propane (25%) LHC 3: Propane (70%), Butane (10%), Naphtha (20%)	2,318,118	58%	1.07
Dow Chemical (Taft, LA)	1,000,000	Unit 1: Ethane (20%), Propane (40%), Naphtha (40%) Unit 2: Not reported	2,343,557	44%	1.03
DuPont (Orange, TX)	680,000	Ethane (100%)	993,914	17%	0.25
Eastman Chemical (Longview, TX)	781,000	Ethane (25%), Propane (67%), Butane (7%), Naphtha (1%)	2,262,549	32%	0.93
Equistar Chemicals (LyondellBasell) (Channelview, TX)	1,750,000	Ethane (5%), Naphtha (95%)	1,886,325	71%	0.76
Equistar Chemicals (LyondellBasell) (Clinton, IA)	476,000	Ethane (80%), Propane (20%)	421,998	43%	0.39
Equistar Chemicals (LyondellBasell) (Corpus Christi, TX)	771,000	Ethane (10%), Propane (30%), Naphtha (60%)	1,170,011	58%	0.88
Equistar Chemicals (LyondellBasell) (LaPorte, TX)	1,189,000	Ethane (60%), Propane (20%), Naphtha (20%)	1,113,490	94%	0.88
Equistar Chemicals (LyondellBasell) (Morris, IL)	550,000	Ethane (80%), Propane (20%)	391,192	79%	0.56
ExxonMobil Chemical (Baton Rouge, LA)	1,000,000	Ethane (9%), Propane (8%), Butane (8%), Naphtha (25%), Gas Oil (25%), Other-Residue (25%)	4,425,161	15%	0.65
ExxonMobil Chemical (Baytown, TX)	2,200,000	Ethane (58%), Propane (8%), Butane (9%), Naphtha (25%)	7,797,812	3%	0.08
ExxonMobil Chemical (Beaumont, TX)	900,000	Ethane (8%), Propane (8%), Butane (9%), Naphtha (75%)	4,708,198	9%	0.47
Flint Hills (Port Arthur, TX)	634,921	Naphtha (60%), Other-LPG (40%)	783,141	53%	0.66
Formosa Plastics (Point Comfort, TX)	1,541,000	Ethane (45%), Propane (15%), Naphtha (40%)	3,721,786	41%	0.99
Huntsman (Port Neches, TX)	180,000	Not reported	902,951	18%	0.89
INEOS Olefins and Polymers USA (Chocolate Bayou, TX)	1,752,000	Ethane (50%), Propane (35%), Naphtha (15%)	2,296,932	53%	0.70

(CONTINUED)

TABLE 5 (CONTINUED)

Greenhouse Gas Emissions from US Ethylene Producers

Plant (location)	2015 Capacity (Mt per year)	Feedstock mix	Total CO_2e Emissions Reported (Mt)	% from Ethane Cracking	Emission Rate (CO_2e from ethylene/ ethylene capacity)
Javelina (Corpus Christi, TX)	151,000	Other-Ref. Gas (100%)	35,393	N/A	N/A
Sasol (Lake Charles, LA)	471,655	Ethane (100%)	636,129	N/A	N/A
Shell Chemicals (Deer Park, TX)	1,179,138	Not reported	3,336,201	25%	0.71
Shell Chemicals Ltd. (Norco, LA)	1,451,247	Ethane (5%), Naphtha (35%), Gas Oil (60%)	2,337,013	26%	0.41
Westlake Petrochemicals (Calvert City, KY)	285,714	Ethane (100%)	373,022	2%	0.03
Westlake Petrochemicals (Sulphur, LA)	1,197,844	Unit 1: Ethane (100%) Unit 2: Ethane (70%), Propane (30%)	857,886	22%	0.16
Williams Olefins (Geismar, LA)	884,354	Ethane (92%), Propane (8%)	347,774	N/A	N/A

Source: USEPA Permits.

FIGURE 9

Planned Petrochemical Production Buildout in the Ohio River Valley

Of 128 existing or potential facilities that are part of a vast buildout of the petroleum and petrochemical industry in the Ohio River Valley, 38 have data available on permitted emissions increases. Shown below, these increases would add 21,866,924 tons per year of CO_2e emissions.

Sources: Proprietary databases and reports from industry and trade press, and datasets maintained by environmental advocacy groups.

are already underway to expand US capacity by at least 13.6 million Mt per year (see Table 6). Six of the 12 projects also involve expanding capacity of other downstream products, like PVC and PE. All but one of these projects (PTT Global Chemical America) have been authorized to begin construction under the Clean Air Act. These projects have the potential to directly emit a total of 21.2 million Mt CO_2e per year.[199] The majority of these new cracker projects are being built along the Gulf Coast of Texas and Louisiana, which is already a major global petrochemical hub. Two of the new projects are located near the Marcellus shale formation in Pennsylvania and Ohio, where the fracking boom is fueling industry plans to create a major new petrochemical hub in the region.[200]

BOX 7

Manufacturing Emissions Daily

The US Department of Energy's National Renewable Energy Laboratory estimated that daily CO_2e emissions from the average petrochemical manufacturing facility were about 1,252 Mt per day in 2014, and 643 Mt per day for plastic manufacturing. Petrochemical manufacturing required average process heat temperatures of 875°C, while plastic material and resin manufacturing required temperatures of 291°C.[201] In total for 2014, 35 petrochemical (ethylene) facilities released 43,806 Mt per day, and 72 plastic manufacturing facilities released 46,324 Mt CO_2 per day.[202]

TABLE 6

US Ethylene Expansions and Potential Emissions Increases

Company (Location)	2015 Ethylene Capacity (Mt/year)	2015 GHG Emissions (tons CO_2e)	New Capacity (Mt ethylene/year, other products specified)	Potential CO_2e Increase (tons/year)
OxyChem/Mexichem (Ingleside, TX)	N/A	N/A	544,000	474,976
Dow Chemical (Freeport, TX)	666,800	2,928,091	1,500,000	2,942,218
ExxonMobil Chemical (Baytown, TX)	2,200,000	8,596,932	1,500,000	1,453,293
Chevron Phillips Chemical (Cedar Bayou, TX)	835,000	1,137,171	1,500,000	1,615,000
Formosa Plastics (Point Comfort, TX)	1,541,000	4,103,006	1,250,000	3,868,872
Sasol (Lake Charles, LA)	471,655	701,239	1,600,000 LDPE: 450,000 LLDPE: 450,000 EO/EG: 300,000 Ethoxylates and detergent alcohols: 300,000	3,955,120
Westlake (Axiall)/Lotte (St. Charles, LA)	N/A	N/A	1,000,000 MEG: 771,617	1,155,059
Shintech (Plaquemine, LA)	N/A	N/A	500,000 PVC: 407,500 Caustic Soda: 800,000 Chlorine: 700,000 Vinyl chloride monomer: 1,200,000 Ethylene dichloride: 750,000	1,403,807
Shell (Monaca, PA)	N/A	N/A	1,500,000 HDPE/LLDPE: 1,100,000 HDPE: 500,000	2,248,293
Total/Borealis/Nova (Port Arthur, TX)	N/A	N/A	1,000,000	1,396,476
PTT Global Chemicals America (Dilles Bottom, OH)	N/A	N/A	1,500,000 HDPE: 650,000 LLDPE: 900,000	1,764,765
Exxon/SABIC (Gregory, TX)	N/A	N/A	1,800,000 PE: 1,300,000 MEG: TBD	2,933,595
Total			**13,694,000 (Ethylene only)**	**23,446,709**

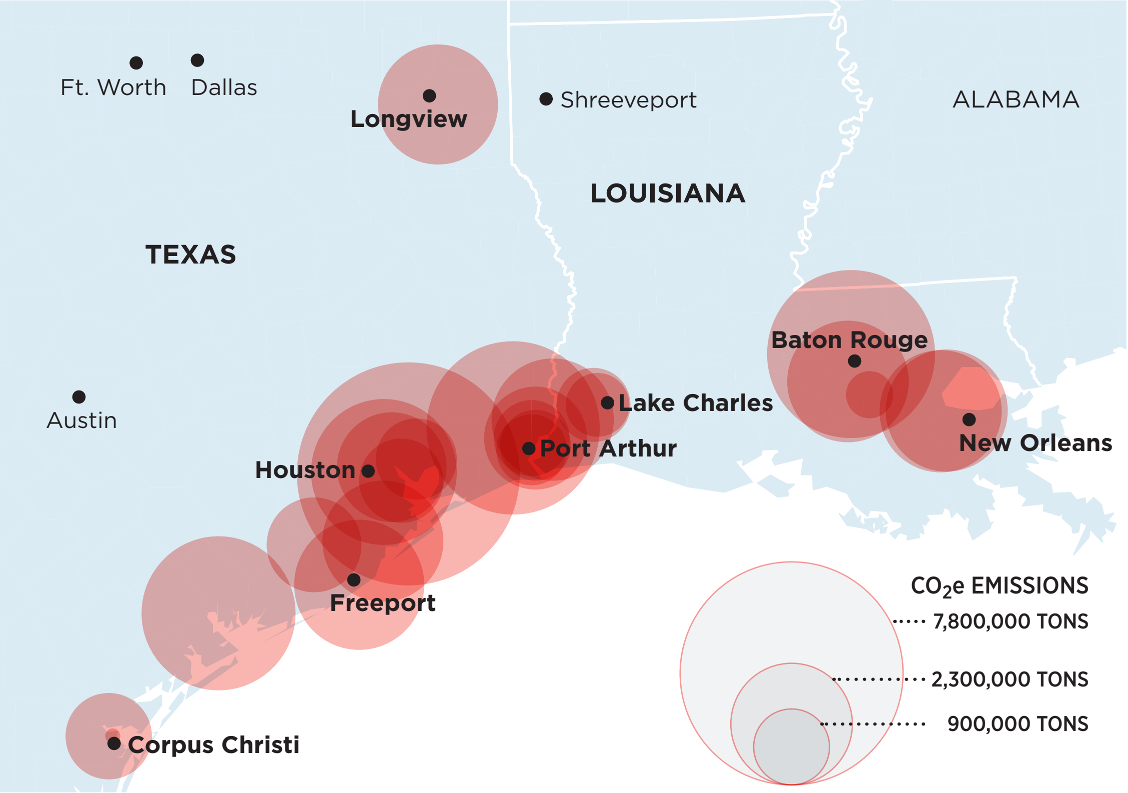
Note: CO_2e increases are from permits and permit applications, which were calculated using AR4 global warming potentials, not AR5. They are also in US short tons, not metric tons.

Sources: USEPA permits; Insights from *First Wave of US Ethylene Projects Drive Second Wave Decisions*, Petrochemical Update (May 5, 2017), http://analysis.petchem-update.com/engineering-and-construction/insights-first-wave-us-ethylene-projects-drive-second-wave-decisions.

FIGURE 10

Emissions from US Gulf Coast Petrochemical Plants that Produce Ethylene

The US had 28 industrial facilities with ethylene crackers in 2015, capable of producing 28.4 million metric tons of ethylene a year. These sites reported total emisions of 53 million metric tons of CO_2e in 2015, though many make of a range of products, so not all of those emissions can be attributed to steam cracking. All but three of these sites were near the Gulf Coast.



Sources: Oil & Gas Journal, Special Report: International Survey of Ethylene from Steam Crackers (2015), https://www.ogj.com/content/dam/ogj/print-articles/volume-113/jul-6/International-survey-of-ethylene-from-steam-crackers--2015.pdf; US EPA, Greenhouse Gas Reporting Program (2015).

RESIN MANUFACTURING

Resin manufacturing processes and energy requirements vary by product and so do their emissions. Certain types of plastic—such as PS and PET—are more energy intensive to produce than others—such as LLDPE, LDPE, HDPE, and PP—because of the additives or catalysts needed in the manufacturing process. Like in cracking, emissions and energy requirements vary by production method and efficiency, as well as plant age and the types of emissions controls used. Growth in US ethylene is fueling an increase in polyethylene production, which is expected to increase from 17 million Mt in 2015 to 23 million Mt (a 35-percent increase) by 2020.[203] US PET production was three million Mt in 2012, with increases expected as a new plant in Corpus Christi, Texas, will add another 1.1 million Mt per year when constructed.

LDPE requires compression to 100-300 megapascals, interstage cooling, and reactor temperatures between 130°C and 330°C. Some process heat can be collected and reused. PET, in contrast, requires additional inputs and energy to produce. Its building blocks are ethylene glycol and terephthalic acid. The former is created from ethylene, and the latter is produced from xylene, hydrogen, and acetic acid. Two processes can be used to create PET: esterification and transesterification. Each process relies on ethylene glycol but different forms of terephthalic acid (purified or dimethyl) and it yields either water or methanol as a byproduct. Polymerization is a two-step reaction that requires temperatures of 260°C and 260-300°C.[204]

Existing Cradle-to-Resin Lifecycle Analysis Estimates

As noted in Chapter 3, the most recent research into cradle-to-resin greenhouse gas emissions for plastic are modeled on emissions factors prepared by Franklin Associates in 2011.[205] Table 7 shows annual greenhouse gas emissions estimates based on 2015 North American resin production, scaled up by 33–36 percent through 2030, holding all else equal. Using these CO$_2$e emission rates, the production of 38 million Mt of the seven most common plastic resins likely resulted in the release of 67.9 million Mt of greenhouse gases in 2015, including emissions from oil and natural gas extraction. This is roughly the equivalent of 15 five-hundred-megawatt coal plants running around the clock for a full year. By 2030, total annual greenhouse gas emissions could expand to as much as 92.4 million Mt, or the equivalent of 20 five-hundred-megawatt coal plants.[206]

As detailed above, these estimates likely underestimate the actual greenhouse gases emitted in 2015. They do not include any indirect emissions, direct emissions associated with plant leaks and malfunctions, or other situations in which emissions may be higher than normal, such as natural disasters.

Opportunities to Reduce Emissions from Plastic Production

Several studies have examined ways to reduce greenhouse gas emissions during this step in the process. Posen et al. argue that manufacturing plants could source their energy from renewable sources where possible and reduce overall greenhouse gas emissions by 50–75 percent at a cost of $85 per Mt of plastic. They could also transition to using bio-based feedstocks, which, in the case of corn-based plastic, could reduce emissions by 25 percent at a cost of $3,000 per Mt of plastic.[207] These are, at best, incomplete solutions. For example, a 2018 analysis by Material Economics suggested that even powering plastic production with 100 percent zero-carbon energy sources would reduce overall emissions by only half.[208]

A 2018 analysis by Material Economics suggested that even powering plastic production with 100 percent zero-carbon energy sources would reduce overall emissions by only half.

IEA makes several broad policy recommendations that might reduce greenhouse gas emissions from petrochemical manufacturing in the long term, assuming that production does not increase from current levels. These include: directly stimulating research and development of sustainable production and methods for limiting risks; establishing and extending plant-level benchmarking, including parameters like energy efficiency and CO$_2$ emissions; creating policies that reduce CO$_2$ emissions; setting stringent air quality standards; and structuring fuel and feedstock subsidies so that they do not inhibit the use of more sustainable alternatives to fossil fuels and feedstocks. Under the best-case scenario outlined by the IEA, reducing greenhouse gases in the long term will also involve increased recycling rates to reduce demand for primary chemicals and feedstocks. Companies will also have to shift to lighter feedstocks and improve energy efficiency by using new technologies

TABLE 7

Cradle-to-Resin Greenhouse Gas Emissions Estimates Based on US Resin Production

Resin	Mean Emissions Factor (unit CO$_2$e/ unit plastic/year)	North American Production (million metric tons, 2015)	2015 CO$_2$e Emissions (million metric tons, 2015)	Assuming 33–36% Production increase (million metric tons per year by 2030)
Polystyrene (PS)	3.1	2	6.2	8.2–8.4
Polyethylene Terephthalate (PET)*	2.4	2.8*	6.7	8.9–9.1
Polyvinyl Chloride (PVC)	2.2	6.7	14.7	19.6–20.0
Low-Density Polyethylene (LDPE)	1.8	3.2	5.8	7.7–7.8
Linear Low-Density Polyethylene (LLDPE)	1.5	6.6	9.9	13.2–13.5
High-Density Polyethylene (HDPE)	1.5	8.6	12.9	17.2–17.5
Polypropylene (PP)	1.5	7.8	11.6	15.6–15.9
Total		**38**	**67.9**	**90.3-92.4**

* PET production is from 2012

Source: Daniel Posen et al., *Greenhouse Gas Mitigation for U.S. Plastics Production: Energy First, Feedstocks Later*, 12(3) *Envtl Res. Letters* (Mar. 16, 2017), *https://iopscience.iop.org/article/10.1088/1748-9326/aa60a7/pdf*.

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like naphtha catalytic cracking, which requires less naphtha than steam cracking.[209]

IEA also suggests that further integration of petrochemical and plastic manufacturing within existing natural gas, oil, and fossil fuel industries would improve efficiency and allow expanded use of carbon capture, usage, and storage (CCUS) technologies.[210] However, CCUS technologies impose significant energy penalties that limit the emissions reduction benefits. Moreover, the most economic uses of carbon capture are likely to result in increased production of oil or combustible fuels that exacerbate emissions.[211] Finally, developing and deploying CCUS projects at scale will require significant new investments in long-lived fossil fuel infrastructure, which is incompatible with the rapid phaseout of fossil fuels required to keep climate change to below 1.5°C of temperature rise.[212]

PLASTIC PRODUCT MANUFACTURING

The plastic manufacturing process is the stage in the lifecycle in which a thermoplastic or resin in pellet form undergoes a series of molding processes to create final products, like single-use containers for fast-moving, consumer-facing brands. For the key plastic manufacturing processes, emissions are released as part of the direct emissions from processing, as well as the indirect emissions from processes that contribute to finished polymers, including PE, PP, and PS.

Plastic packaging represents 40 percent of total production of plastic products.[213] Plastic packaging is typically single-use, ubiquitous, and extremely difficult to recycle. Bottles, bags, wraps, and films comprise the largest packaging segments by revenue.[214] According to the United Nations Environment Programme (UNEP), the negative impacts of plastic packaging are estimated at $40 billion and expected to increase with significantly expanded production under a business-as-usual scenario.[215]

Recommendations for Reducing Emissions in Plastic Manufacturing

Proponents of the circular economy advocate for developing business models and industry structures to greatly increase the usable lifespan of products and materials, dramatically reduce material production and the consumption of raw materials, and reduce the greenhouse gas emissions that arise from unnecessary production, consumption, and waste disposal.[216] For the manufacturing of plastic, this includes policies and initiatives that address:

Materials Reduction: Curtail and reduce the unnecessary or excessive use of materials, through changes in processes, products, or behaviors. In the plastic context, this would include initiatives to ban or curtail the use of non-essential plastic, including single-use disposable plastic commonly found in packaging, food and beverage service, and fast-moving consumer goods.

Materials Recirculation: Develop the policies, technologies, and systems necessary to reduce waste and decrease reliance on virgin materials by ensuring products are designed and managed throughout their lifecycles for reuse and continual recycling (rather than downcycling). These processes include setting and reinforcing standards to regulate waste and improving the design and end-of-life handling of products. At present, strategies for materials recirculation face significant systemic challenges, which are discussed in Chapter 6. Accordingly, simple pledges to increase recycling rates, even dramatically, are unlikely to address either the material or the climate impacts of growing plastic production.

Product Material Efficiencies: Ensure greater use for materials and incentivize reuse and recycling through target initiatives intended to improve product materials through greater transparency, technology, and information.

Circular Business Models: Stimulate reuse as a way to support fewer products for the same benefit, service, or output. Developing business models that increase use while prolonging the lifetime of materials-intensive assets could reduce emissions by 62 million Mt CO_2 per year.[217]

These processes include adopting greater energy efficiency technologies in the manufacturing process, improving design and management of raw materials, and fostering greater use and reuse by the largest consumer-facing producers. Reducing waste in production, extending the lifetime of products, and deploying new business models could produce rapid and significant improvements in both waste streams and greenhouse gas emissions. Adopting circular economy strategies alone, however, is unlikely to outpace the scale and rate of petrochemical infrastructure expansion. For example, the American Chemistry Council is also ostensibly embracing the circular economy approach by making statements that resin producers aim to recycle or recover 100 percent of plastic packaging by 2040.[218] Such statements obscure the fact that the intended path towards achieving such goals include accelerating plastic production that would be "balanced out" by dramatically increasing incineration, as a form of plastic "recovery."

On average, the production of one ton of plastic resin will emit 1.89 Mt CO_2e. When the differing emission profiles in the US and Europe are taken into account, producing a ton of PE will release 1.675 Mt CO_2e; PP, 1.55 Mt; PET, 2.275 Mt; PVC, 2.095 Mt; and PS, 3.2 Mt.

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CHAPTER SIX

Plastic Waste Management

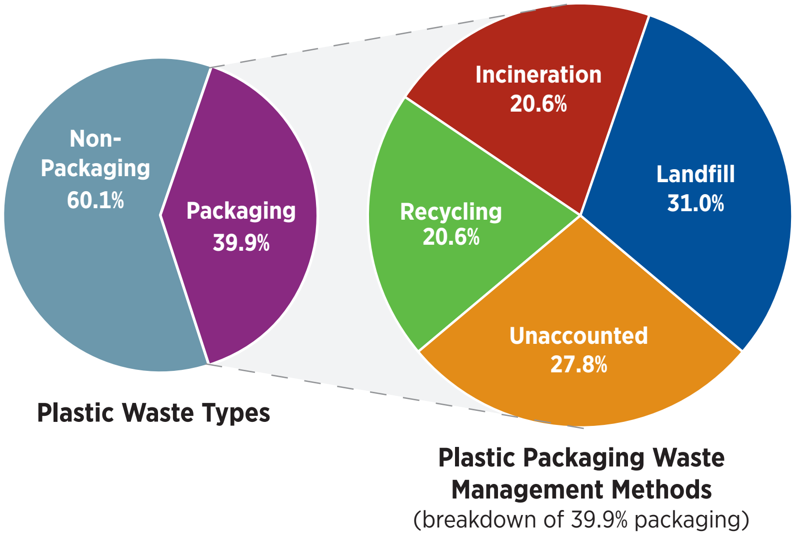
"END OF LIFE" IS NOT END OF IMPACT

As previous chapters demonstrate, the direct and indirect greenhouse gas emissions from plastic production, transport, refining, and manufacture are significant. Yet the climate impact of plastic does not end after the plastic has been used and is discarded. Depending on how it is handled, plastic can pose just as significant a threat to the climate when it reaches the waste phase of its lifecycle. For most materials, this stage is often referred to as "end of life." In truth, because plastic continues to pollute long after its useful "life" is over, there is increasing understanding that there is no such thing as an "end of life" for plastic.

This chapter aims to shed light on the climate impact of plastic after it is used, examining direct and indirect greenhouse gas emissions and emissions offsets at the disposal stage of the plastic lifecycle. As no contemporary research provides quantitative estimates for greenhouse gas emissions from different plastic waste management methods, Sound Resource Management Group undertook modeling and data analysis specifically for this report. The analysis provides the current status and future prospects of greenhouse gas emissions from incineration, disposal at landfills, and recycling, based on existing estimates of worldwide plastic generation and disposal. The scope of this analysis is adjusted to plastic packaging, due to the lack of data on the composition of all plastic waste at a global level. A detailed description of the research methodology and relevant sources are online at *http://www.no-burn.org/plastic-climate-appendix*.

FIGURE 11

Global Plastic Packaging Waste Management, 2015



Known Paths of Plastic Waste

While some plastic can be recycled, doing so involves many steps that require separate collection, long-distance transportation, processing, and re-manufacture. The high costs of these steps, the low commercial value of recycled plastic, and the low cost of virgin material mean that plastic recycling is rarely profitable and requires considerable government subsidies. Due to these limitations, only nine percent of all plastic ever discarded since 1950 has been recycled, while another 12 percent has been incinerated.[219] The remaining plastic has been buried or ended up in open yards for burning and dumping, in oceans and other waterways, and scattered across human and natural landscapes worldwide.

Regardless of disposal method, all discarded plastic represents a danger to human health and the environment. Whenever plastic is burned, it emits greenhouse gases, principally CO_2. Plastic

Opposite: © Claire Mortimer/Greenpeace

FIGURE 12

Generation, Recycling, and Disposal of Plastic in the US, 2015

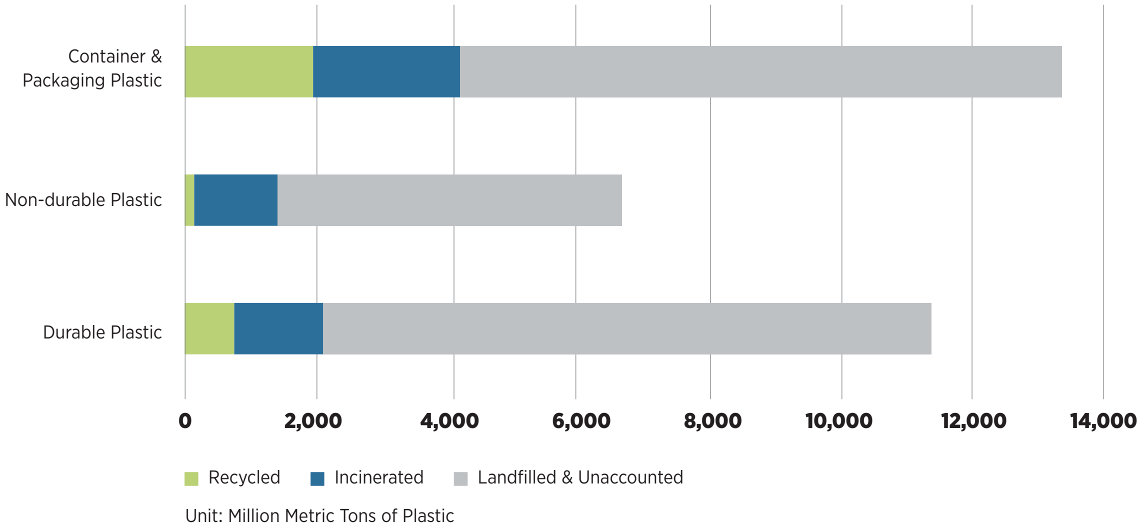


TABLE 8

1960–2015 Data on Plastics in MSW by Weight (in thousands of US tons)

Management Pathway	1960	1970	1980	1990	2000	2005	2010	2014	2015
Generation	390	2,900	6,830	17,130	25,550	29,380	31,400	33,390	34,500
Recycled	—	—	20	370	1,480	1,780	2,500	3,190	3,140
Composted	—	—	—	—	—	—	—	—	—
Combustion with Energy Recovery	—	—	140	2,980	4,120	4,330	4,530	5,010	5,350
Landfilled	390	2,900	6,670	13,780	19,950	23,270	24,370	25,190	26,010

Sources: American Chemistry Council and the National Association for PET Container Resources. A dash in the table means that data is not available.

also contains hazardous chemicals in the form of additives that are released into the environment. Concentrations and quantities of these pollutants vary depending on how plastic waste is handled. The human health impacts of plastic incineration are reviewed in greater detail in the companion report *Plastic & Health: The Hidden Costs of a Plastic Planet.*

In the US, plastic waste in municipal solid waste (MSW) streams is managed by recycling, landfilling, and burning in waste-to-energy facilities. Plastic waste managed in MSW amounted to 34.5 million tons in 2015, comprising about 13 percent of total MSW generated that year.[220] As indicated by the estimates from USEPA for 2015 shown in Figure 12,[221] landfilling was the primary handling method for plastic waste, accounting for 75.4 percent. The remainder was either incinerated (15.5 percent) or recycled (9.1 percent). For non-durable and container/packaging plastic, the proportion incinerated was greater than for durable plastic.

An unknown amount of plastic packaging waste in the United States is mismanaged, primarily via littering and open burning.[222] The mismanagement rate is relatively low, compared to other countries with lower waste collection and processing capacity, which often leads to an assumption that low-income countries are responsible for unmanaged waste leaking into oceans and lands. However, high per-capita waste generation and large coastal populations result in a large mass of uncontrolled plastic waste even when rates of mismanagement are low, as shown in one study that estimated that the US is among the major contributors to plastic ocean leakage.[223]

Plastic Packaging Waste

Plastic packaging represents 40 percent of total production of plastic products.[224] Packaging is one of the most problematic types of plastic waste, as it is typically designed for single use, ubiquitous in trash, and extremely difficult to recycle. A constant increase in the use of flexible and multi-layered packaging has been adding challenges to collection, separation, and recycling. Figure 10 on page 55 shows current plastic packaging waste management methods in use worldwide. While 40 percent of plastic packaging waste is disposed of at sanitary landfills, 14 percent goes to incineration facilities, and only 14 percent was collected for recycling, 12 percent of which failed to be recycled into the same or similar quality of the original form.[225] The remaining 32 percent follows other pathways, including open dumping, open burning, and uncontrolled release onto land and into water.[226]

In Europe, efforts to divert plastic packaging waste from landfills have accelerated over the past decade, showing an increase in recycling and incineration with energy recovery.[227] The trend is more distinct among countries that implement bans on landfilling recyclable waste, most of which tend to heavily rely on waste incineration with energy recovery.[228] In the following sections, the climate impact of growing dependence on waste incineration is examined under a series of possible future scenarios.

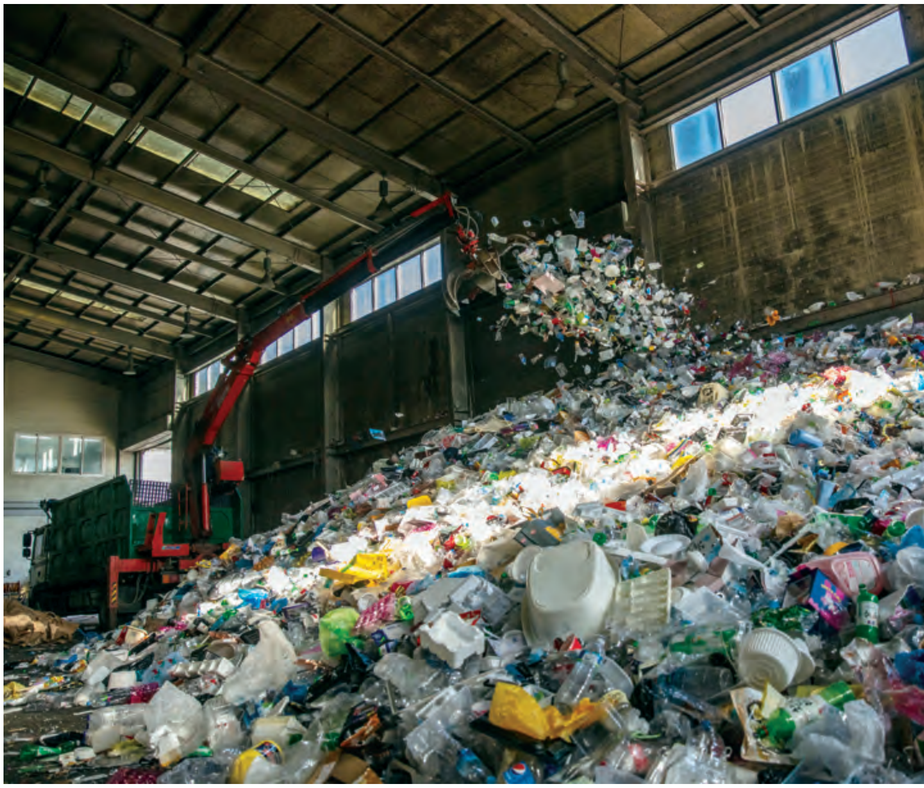
GREENHOUSE GAS EMISSIONS FROM PLASTIC WASTE DISPOSAL

There are several ways of managing plastic waste, each of which has clear implications for the climate. As stated earlier, this analysis compares greenhouse gas emissions from recycling, landfilling, and incineration with energy recovery, based on the data available for plastic packaging waste. Key parameters and estimates factored into this analysis include annual plastic production in 2015, plastic packaging portion of total plastic production (39.9 percent in 2015), polymeric composition, and combustible carbon content plastic packaging, which enable estimating of carbon emissions from power generation and potential emissions offsets though energy recovery. Indirect greenhouse gas emissions from energy use for materials handling and waste collection were calculated to quantify the climate impact of plastic waste throughout the disposal process. In order to estimate net greenhouse gas emissions from plastic recycling, emissions offsets from replacing virgin material production with recycled content were calculated. For estimates of greenhouse gas emissions offsets resulting from energy recovery, the analysis applies a conservative estimate from the EIA of the current and future ratios of natural gas and renewable energy in the energy mix. Detailed references and assumptions are available at: *http://www.no-burn.org/plastic-climate-appendix*.

As shown in Figure 13, incineration, including waste-to-energy, creates the most CO_2 emissions among the plastic waste management methods. Waste collection, hauling, and processing also create climate-changing greenhouse gas emissions, mainly due to energy use. These various waste management methods are discussed in more detail in the following sections, beginning with the most intensive emissions-producing processes first.

Waste Incineration and Waste-to-Energy

Incineration is often thought of as an easy answer to large-scale, land-based plastic pollution. Frequently touted for its ability to turn waste to energy, incineration converts waste into air pollutants, bottom ash, fly ash, combustion gases, wastewater, wastewater treatment sludge, and heat by burning. In urban areas, incineration of waste occurs at waste-to-energy (WTE) facilities and other industrial facilities, including utility



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boilers, paper mills, and cement kilns, in which collected wastes are burned with coal or biomass in a process known as co-incineration.

As Figure 13 depicts, one Mt of plastic burned results in 0.9 Mt of net CO_2e emissions, even after taking into account the electricity generated by the combustion process. On average, one Mt of plastic packaging contains 79 percent combustible carbon content,[229] which would release 790 kg of carbon, or about 2.9 Mt of CO_2, into the atmosphere.[230] The USEPA recognizes that net greenhouse gas emissions can be reduced through energy recovery by offsetting the need for energy from fossil sources. Accordingly, USEPA's analysis quantified the power generation potential for plastic packaging burned in MSW in a WTE facility by multiplying average energy content of plastic packaging waste by an average electricity output efficiency for WTE incinerators of 17.8 percent.[231] The estimated power generation potential of less than 2,000 kilowatt hours (kWh) per Mt was further converted to natural gas and renewable energy offsets based on EIA estimates for worldwide electricity generation, to reach a conclusion that incineration of plastic packaging waste will still result in 0.9 Mt of CO_2e emissions, even when two Mt of CO_2e can be offset by energy recovery.

The greenhouse gas emissions offset potential can vary depending on a number of factors, including the type of energy used in the incinerators and the composition of waste feedstock that is burned. When municipal solid waste is too low in calorific value and/or too high in moisture content, additional fossil fuels are required to sustain the combustion. For example, in China, the ratio of coal in the fuel used in MSW incinerators is as high as 50-70 percent due to the large portion of organic waste.[232]

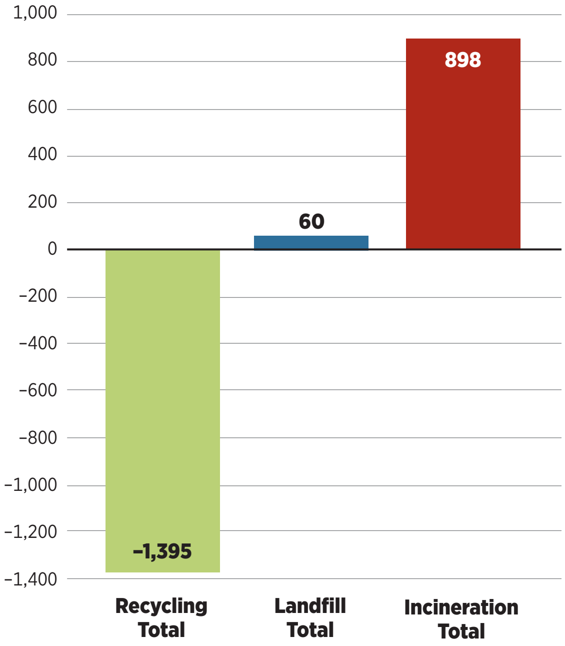
According to our analysis, net greenhouse gas emissions attributable to the incineration of plastic packaging are estimated to be 16 million Mt in 2015. These figures are based on the estimated amount of plastic packaging waste (40 percent of all plastic waste) collected for management (64 percent); thus, it reflects only 25 percent of all plastic waste. For a broader plastic waste stream, including plastic packaging and non-packaging plastic waste, USEPA reported that waste incineration released 11 million Mt CO_2e in the US, more than half of which came from plastic waste (5.9 million Mt) in 2015.[233] The climate impact of plastic waste incineration in the US is equivalent to 1.26 million passenger vehicles driven for one year, or more than half a billion gallons of gasoline consumed.[234]

When plastic packaging waste commingled in MSW is burned in a WTE incinerator, the generated electricity replaces power generated from other

FIGURE 13

Climate Impacts of Plastic Packaging Waste Disposal Options (kg CO_2e/metric ton)

Activities/Processes	Recycling	Landfill	Incineration
Collection/Self-Haul	45	35	35
Material Handling	650	25	38
Virgin Material Offset	–2,090		
Biodegradation		0	
Incineration			2,894
With Energy Recovery			
Natural Gas Offsets			–2,040
Renewable Energy Offsets			–30
Total	**–1,395**	**60**	**898**



Note: This analysis assumes that all incineration is conducted with energy recovery, as exact data on the ratio of incineration without energy recovery is currently not available. While incineration without energy recovery does exist, it results in 2,894 kg CO_2e of greenhouse gases per Mt of plastic burned, which is the same as open burning. US EIA, International Energy Outlook, 2017 (data for 2015) estimates that renewable energy accounted for 17 percent of worldwide electricity generation in 2015.

Source: Sound Resource Management Group, Inc provided this analysis based on the sources available at *https://www.no-burn.org/plastic-climate-appendix*.

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fuels. In many cases, this will be natural gas because natural gas turbines are often used for peaking power on electrical power grids, or are often the type of energy used in power generation facilities that are the next in line for construction. To an ever greater degree, new power production also comes from renewable solar or wind energy facilities. According to the EIA, in 2015, natural gas combustion produced almost five times as much electricity worldwide as did renewable solar, wind, and geothermal energy.[235] This ratio was used to calculate the WTE greenhouse gas offsets for natural gas and renewable solar. Those calculations also take into account the relative fossil carbon footprints of electricity generated from renewable solar, natural gas, and packaging plastic waste.[236] As the proportion of renewable energy in the energy mix continues to grow over the coming decades, the net emissions from incinerating plastic will increase as electricity production will be less dependent on fossil fuels, resulting in smaller emissions offsets. An analysis of lifecycle plastic emissions in Europe undertaken by Material Economics concluded that, as this energy transition occurs, the incineration of plastic waste will become one of the largest sources of fossil fuel emissions in Europe's energy sector.

In 2015, USEPA reported plastic waste incineration released 5.9 million Mt CO_2e. As the energy transition occurs, the incineration of plastic waste will become one of the largest sources of fossil fuel emissions in Europe's energy sector.

The climate impact of plastic waste management will increase even more dramatically if industry's plans to increase incineration and expand petrochemical buildout by 2030 and 2050 come to fruition. The continuing decarbonization of the energy mix will also result in an increase in the proportion of net greenhouse gas emissions from the incineration of plastic packaging. As a result, greenhouse gas emissions from plastic packaging waste are projected to reach 84 million Mt and 309 million Mt by 2030 and 2050, respectively. (See Figure 14.)

BOX 8

Future Scenarios of Greenhouse Gas Emissions from Plastic Packaging Waste Incineration with Energy Recovery

THE INDUSTRIAL OUTLOOK

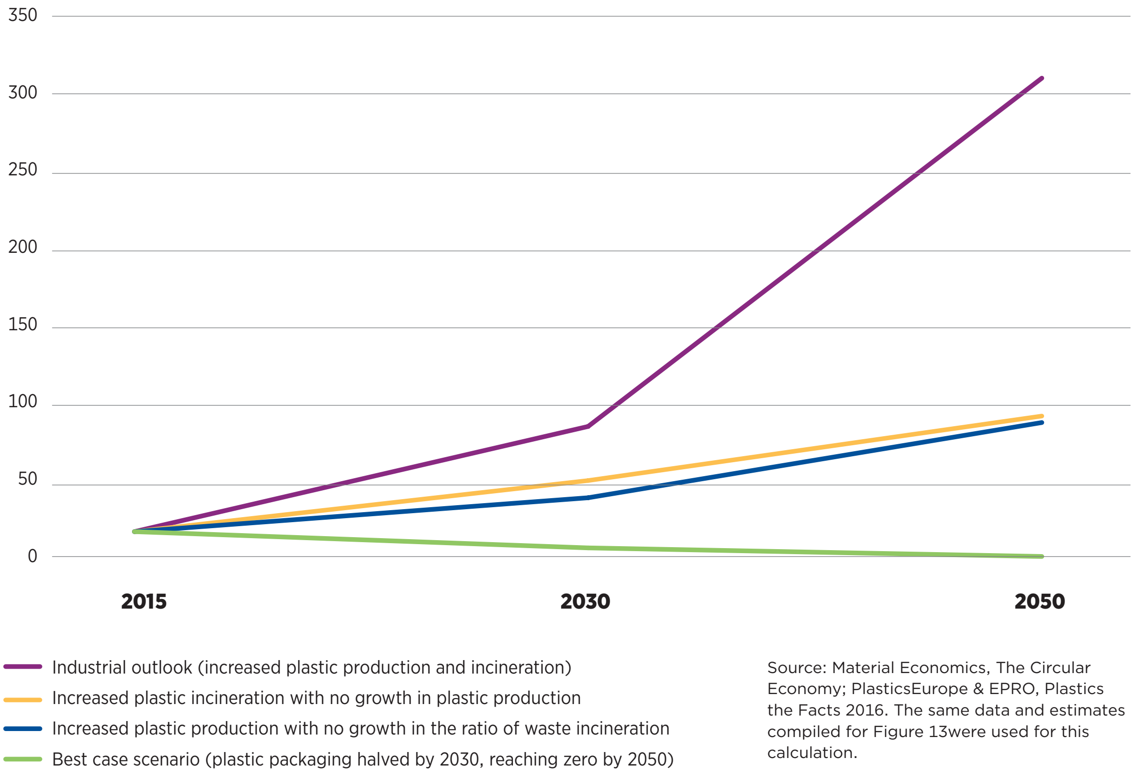
This scenario factors in the growth in plastic packaging production and the expansion of incineration capacity based on industry projections. According to several sources, plastic packaging production is expected to nearly double by 2030 or 2035 and nearly quadruple by 2050.[237] The present analysis estimates that this growth would increase plastic packaging waste from 128 million Mt in 2015 to 219 million Mt by 2030 and 435 million Mt by 2050. Greenhouse gas emissions from incineration of plastic packaging waste would grow correspondingly to 84 million metric tons by 2030 and 309 million metric tons by 2050. The faster growth in carbon emissions relative to plastic packaging waste is due entirely to faster growth in electricity generated from solar, wind, and geothermal energy versus natural gas and the corresponding fall in the carbon offsets for WTE, which was applied to all of the following cases.

INCREASED INCINERATION WITH NO GROWTH IN PLASTIC PRODUCTION

A recent study on world energy resources by the World Energy Council projected a greater than ten percent compound annual growth rate for waste-to-energy incineration between 2015 and 2025.[238] Assuming that WTE grows at above ten percent through 2030, WTE incineration would increase to 31 percent of treatment for all plastic packaging waste by 2030. Extending this scenario to 2050 assumes a somewhat slower growth of WTE after 2030, in which case 50 percent of plastic packaging waste is managed by WTE by 2050. This case shows that greenhouse gas emissions from

FIGURE 14

Future Scenarios of Greenhouse Gas Emissions from Plastic Packaging Waste Incineration with Energy Recovery



Unit: Million Mt CO_2e/year

Source: Material Economics, The Circular Economy; PlasticsEurope & EPRO, Plastics the Facts 2016. The same data and estimates compiled for Figure 13were used for this calculation.

plastic incineration would increase to 49 million Mt by 2030 and 91 million Mt by 2050, even when the total amount of plastic produced stays at the current level.

INCREASED PLASTIC PRODUCTION WITH SIMILAR INCINERATION RATE

Greenhouse gas emissions from plastic incineration would grow at a similar rate as the previous case if plastic production increases in line with industry projections, along with a slower growth of WTE. The present analysis assumes that the ratio of waste incineration as a waste management method will remain at 14 percent, which means WTE facilities expand proportionately to the growth rate of plastic production; this is less growth than the "industrial outlook" scenario. In this scenario, greenhouse gas emissions from plastic incineration will increase to 38 million Mt by 2030 and 87 million Mt by 2050.

THE BEST-CASE SCENARIO WITH SIGNIFICANT DECREASE IN PLASTIC PRODUCTION AND INCINERATION

These projections also include a best-case scenario for a future in which the use of plastic packaging is cut in half by 2030 and reaches zero by 2050, ultimately resulting in zero emissions from incineration of plastic packaging. The greenhouse gas emissions from this scenario would be as low as six million Mt by 2030 and zero by 2050. This last set of projections are guided by targets set as part of the New Plastics Economy Global Commitment—which was signed by more than 290 companies to eliminate problematic or unnecessary plastic packaging by 2025[239]—and Break Free From Plastic's goal of drastically eliminating all non-essential uses of plastic by 2035, following a peak of plastic packaging and other single-use disposable applications in 2025.[240]

BOX 9

Future Outlook on the US Energy Grid and the Implications on Greenhouse Gas Emissions Offsets

Electricity generation methods gradually evolve. That is, based on US Energy Information Administration projections for worldwide electricity generation through 2040,[241] the relative amounts of electricity produced from renewable solar, wind, and geothermal energy will rise relative to electricity production from natural gas. Currently, natural gas fuel generates 4.9 times as much electricity as the aforementioned renewables. In a conservative manner, EIA projects that this ratio will decrease to 2.1 by 2030 and continue decreasing at a slower rate through 2040. Assuming this slowdown continues, by 2050 natural gas would generate only 150 percent more electricity than the three renewables. This decreases the energy offset for waste-to-energy incineration of plastic packaging wastes, lowering the natural gas and renewables weighted average offset from 2,070 kg CO_2e per Mt of incinerated plastic in 2015 to 1,728 kg CO_2e by 2030 and 1,545 kg CO_2e by 2050.

In a future with 100 percent renewable electricity, there would be almost no carbon offsets for WTE electricity generation from burning plastic packaging waste. Even at present, carbon emissions per kilowatt generated from WTE incineration of plastic waste are not low enough to beat natural gas carbon emissions per kilowatt hour. That is, WTE incineration of plastic packaging waste is over 20 percent higher in carbon emissions per kilowatt hour than natural gas. Compared to renewables, the carbon emissions from WTE are greater by an order of magnitude. For example, solar electricity is almost 17 times more efficient than WTE incineration of plastic packaging waste for generating electricity. Thus, as electricity supplied to the power grid by renewables increases relative to natural-gas-fueled power, the net emissions from WTE incineration of plastic packaging increases from about 900 kg CO_2e per Mt of incinerated plastic at present to over 1,400 kg CO_2e per Mt of incinerated plastic by 2050.

It is likely that the net emissions from WTE will be significantly greater because the offsets of natural gas are almost certainly overestimated. Over the last decade or more, renewable energy deployments have routinely and substantially exceeded long-term forecasts by both EIA and IEA.[242] This trend has continued in recent years, suggesting that the proportion of fossil fuels in the global energy mix may decline much faster than EIA estimates. Moreover, as noted in the introduction to this report, the IPCC warns that global net emissions of CO_2 must fall to zero by 2050. The IPCC noted that achieving this goal will require the near complete elimination of fossil fuels from energy production and a transition to a renewable energy economy in the coming decades.[243]

BOX 10

Unknown Climate Impact of Plastic-to-Fuel

Gasification, pyrolysis, and plasma arc are other forms of waste incineration, which convert waste into synthetic gas or oils through combustion or other thermal processing. Plastic-to-fuel is a common name for these undefined technologies, which aim to convert all carbon-based materials into energy.[244] Studies sponsored by the American Chemistry Council argue that there are energy and environmental benefits associated with producing high-quality fuels in this manner.[245] Despite aggressive public relations campaigns and construction attempts, there are few facilities successfully operating on a commercial scale. Industry has recorded years of delays and high-profile failures due to operational inexperience, high costs, lack of financing, and environmental concerns around the globe.[246] Due to a lack of empirical data from commercial operations, the greenhouse gas emissions remain unquantified. The fuel produced through this technology is yet another fossil fuel, and the industry will need to prove self-claimed climate benefits by measuring indirect emissions from energy use and the emissions from burning final fuel products, as well as direct greenhouse gas emissions from the combustion process.

Landfilling

In this analysis, landfills refer to sanitary landfills that typically use a clay and/or plastic liner to isolate waste from groundwater and add a daily covering of soil to reduce the waste's exposure to air. Greenhouse gas emissions from landfills are mainly derived from organic waste, such as discarded food, yard trimmings, paper, and wood as they decompose. Landfill wastes of fossil origin have not been documented to emit greenhouse gases, nor are they counted as a carbon sink. Therefore, emissions related to landfilling plastic packaging result primarily from the fossil fuel use associated with the sorting and handling of the wastes prior to landfilling and the transportation of the waste from the collection point to the landfill. This does not exclude the possibility of greenhouse gas emissions from fires in the landfills, however, as an average of 8,300 fires are reported from landfills in the US alone each year.[247]

While landfilling poses significant environmental health risks due to toxic substances leaching into soil and waterways and its emissions from biogenic waste degradation, landfilling plastic waste has lower climate impacts than incineration, as shown in Figure 13. In some cases, landfilling—or dumping waste in an open yard—may be the only option for waste management when there is

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no collection system and no proper material recovery infrastructure in place. However, landfills produce acids by decomposing organics and leach heavy metals out of plastic into the groundwater and therefore cannot be viewed as a long-term solution for plastic waste management.[248]

Recycling

Plastic recycling refers to physical processes that recover materials without altering the molecular structure of the polymers. As Figure 13 demonstrates, plastic recycling has outstanding greenhouse gas benefits compared to other existing waste disposal methods. Making new products from recycled plastic packaging materials is more than three times more efficient in terms of greenhouse gas emissions than manufacturing those same products with virgin raw materials, mainly because of the energy savings in recycled versus virgin-content product manufacturing. For the 3.17 Mt of plastic waste recycled in the US in 2014, USEPA estimates 3.2 million Mt of CO_2e savings, which is equivalent to 670,000 less cars on the road over the course of a year.[249] Recycling a metric ton of plastic packaging into new products conserves almost 1.4 Mt CO_2e.

Theoretically, increased recycling results in negative greenhouse gas emissions by reducing raw material extraction and avoiding emissions from manufacturing an equivalent amount of material from virgin inputs. Emissions per ton of virgin plastic produced are estimated to be 3.6 times higher compared to recycling as of 2017.[250] This gap is estimated to widen to as much as 48 times higher by 2050, as efficiency in both plastic production and recycling improves.[251]

In reality, only a fraction of "recyclable" used plastic is recycled into the products for which they were originally produced, even in the case of the most readily recyclable plastic such as PET and HDPE.[252] The challenges are due to colorants, additives, and fillers used during plastic production, contamination from consumer use, and yield losses during the recycling process.[253] The low price of overproduced virgin plastic further limits the recyclability of plastic by lowering the economic value of recycled plastic and hindering investments in proper infrastructure and markets.[254] Even if plastic were recycled despite all the barriers above, each cycle of the recycling process shortens the length of polymer chains, resulting in quality loss and, eventually, the need to dispose of the material.[255] Lower-grade plastic waste, including post-consumer and multi-layered plastic packaging is particularly difficult to separate and process, which explains why the major plastic-consuming nations in Europe and North America have relied on international trade for plastic recycling, rather than processing plastic scrap at their own labor and environmental cost.[256]

With these limitations, recycling alone will not reduce greenhouse gas emissions from the plastic lifecycle commensurate with the reductions necessary to meet the Paris Agreement. Nevertheless,

BOX 11

Opportunities and Threats of China's Waste Import Ban

In January 2018, the Chinese government banned the import of waste to stop the overwhelming flow of low-grade plastic scrap being shipped to China from the Global North.[257] This ban has had a significant impact throughout the world and highlighted the urgent need to reshape local recycling systems and global policies on plastic production and disposal. The new waste policy bans imports of 24 types of solid waste, including post-consumer plastic, and strengthens contamination control rules for recyclables, rendering much plastic scrap sub-standard.

Local recycling systems, as well as the global recycling trade, have experienced upheaval since the ban was implemented, especially in countries that relied heavily on exporting low-grade plastic scrap for processing. In the United States, facilities in Arizona, Arkansas, Colorado, Hawaii, Maryland, Missouri, and New Jersey reported that they have stopped accepting mixed plastic scrap or have restricted collection to certain types of plastic (mostly PET and HDPE).[258] Scheduled shipments have been held, and material recovery facilities are stockpiling collected waste in many places. Instead of using the ban as an opportunity to consider building a domestically sustained recycling system and working to phase out single-use plastic and plastic packaging, many cities are exploring alternative destinations that can accommodate their waste, which prompted Vietnam, Thailand, and Malaysia to announce their own restrictions on plastic scrap imports.[259] Waste incineration has also been an option for some cities in the US, sparking community organizing against sending recyclables to incinerators.[260] Furthermore, communities are actively guiding cities to respond to the current disruption in domestic plastic recycling with zero-waste approaches focused on reduce and reuse. One example is an ordinance that was recently passed by the City Council of Berkeley, California, to curb disposable foodware.[261]

many studies continue to rely on plastic recycling as a primary solution to the plastic crisis. The Material Economics report states that the ideal scenario for plastic waste management in 2050 can be achieved by increasing plastic recycling capacity by 4.6 times, enabled by a collection rate of 85 percent for the five most common types of plastic, along with a six percent increase of waste-to-energy and more reuse practices. A recent report published by the Organisation for Economic Co-operation and Development and IEA also projects a 65 percent increase in production of recycled plastic compared to the baseline scenario by 2030 and an increase of more than double by 2050.[263]

BOX 12

Plastic Chemical Recycling: A False Solution to the Plastic Waste Crisis

Chemical recycling is a process that chemically transforms materials into their basic components with the purpose of reproducing the same material. While thermochemical and catalytic conversion technologies have been developed for some waste plastic, it is hard to estimate the greenhouse gas emissions associated with the use of high-temperature treatment and plastic solvents. In addition, the plastic industry often conflates chemical recycling with plastic-to-fuel technologies under the guise of terms like "plastic recovery."

For example, in May 2018, the American Chemistry Council announced a plan to ensure 100 percent of plastic packaging would be reused, recycled, or recovered by 2040, with an interim goal of making plastic packaging recyclable or recoverable by 2030.[262] This pledge, while appearing to be a step toward sustainability at face value, raises more questions than answers. The American Chemistry Council's plan to recover plastic includes a variety of technologies, such as pyrolysis, gasification, and other plastic-to-fuel systems (see Box 10: Unknown Climate Impact of Plastic-to-Fuel). Since this technology is relatively new and commercial operations are extremely limited, the greenhouse gas emissions impact of this form of plastic recycling remains unknown. In addition to unanswered questions about the feasibility of these techno-fixes, managing plastic waste through energy-intensive thermal processing to produce more oil and gas is hardly a solution that fits into a circular economy, and it does not recover materials to their original form. Furthermore, as the volume of unrecyclable plastic grows, a timeline much shorter than 2040 is needed to immediately curb plastic pollution.

Other Known Unknowns

The analysis above only covers plastic packaging that is collected for management, leaving the climate impact of almost one-third of world plastic packaging undefined. There are several possibilities for the unmanaged 32 percent of plastic packaging, including open burning, open dumping, and littering, which are more prevalent in rural areas or places with less developed waste management infrastructure.

Open burning, a practice of burning unwanted combustible materials in nature or in open dumps, has severe climate and health impacts because it is undertaken in the absence of air pollution controls and because it generally occurs at much lower temperatures compared to closed combustion environments.[264] Plastic packaging burned in the open releases 2.9 Mt CO_2e of greenhouse gases into air per ton of plastic packaging.

The climate impact of dumping waste into an open hole in the ground (open dumps) without extra effort to compact or cover it up is less defined. As discussed in Chapter 7, degrading plastic exposed to sunlight in terrestrial environments may off-gas greenhouse gases at a higher rate than plastic at the ocean's surface. Consistent with these findings, research conducted in 2018 showed that plastic packaging waste in open dumps or littered onto land or in water emits greenhouse gases over time due to exposure to ambient solar radiation.[265] However, as the annual rate and magnitude of these releases have not as yet been well researched, this study does not include an estimate for these greenhouse gas emissions.

Despite evident data gaps with respect to many of these disposal pathways, exploring a range of added greenhouse gas emissions from the unmanaged portion can cast light on the full scope of threats caused by plastic packaging waste. The climate impact of unmanaged plastic waste largely depends on the proportion that is burned, which can result in 118 million Mt of additional emissions in the case of 100 percent open burning of all unmanaged plastic packaging waste. On the other end of the range, a case of 100 percent littering or open dumping will result in slow but potentially continuous greenhouse gas emissions, and contribute to other areas of environmental concern.

AN ALTERNATIVE PATH: ZERO WASTE

The industry's plans to massively expand the petrochemical buildout and increasingly rely on incinerators are incompatible with the urgent need for dramatic global reductions in greenhouse gas emissions. Fortunately, burning waste is not the only path forward, and the zero-waste approach is gaining traction. Zero waste refers to a systemic approach to waste prevention and reduction. Key components of this approach include decentralized separated collection, sorting and reuse of waste, and an iterative evaluation process that enables communities to assess the waste stream and implement policies to reduce the production and consumption of materials that are hard to recover, such as bans on single-use plastic items. Zero-waste systems aim to return all materials to the community as a resource without being processed in incinerators or landfilled.

The climate benefits of zero waste are clear: non-essential plastic packaging would be eliminated entirely,[266] resulting in no emissions from downstream waste management. The following section outlines three recommendations for alternative zero-waste implementation as part of climate change mitigation strategies.

Use Less Plastic

Plastic packaging, which continues to be produced, used, and discarded at alarming rates, already outpaces all existing waste processing methods due to the unprecedented amount produced, its complex multi-layer construction, and consumer use contamination. Due to the limitations of plastic recycling, phasing out plastic packaging must be prioritized to prevent today's substitution from becoming tomorrow's problems.[267] A boom of investment in the construction and expansion of plastic recycling infrastructure could unintentionally sustain a single-use, linear economy by providing downstream measures to deal with current or even increased plastic production and use. Plastic recycling should, therefore, only be used as a bridge to greater plastic reduction, and as the production of plastic decreases over time, so too should recycling. The highest priority should be developing zero-waste systems where all materials are produced and consumed respon-sibly within ecological limits.

Waste prevention coupled with reduced plastic production is by far the most effective way to reduce greenhouse gas emissions from plastic waste.[268] Source reduction—the waste industry term for less production and consumption—greatly contributes to reducing greenhouse gas emissions from raw material acquisition and manufacturing, resulting in no emissions from waste management.

Plastic packaging, which continues to be produced, used, and discarded at alarming rates, already outpaces all existing waste processing methods due to the unprecedented amount produced, its complex multi-layer construction, and consumer use contamination.

Source reduction avoids greenhouse gas emissions throughout the lifecycle. The USEPA has examined the greenhouse gas benefits of halving the annual generation of plastic packaging in 2006. If, instead of producing 14 million Mt of plastic packaging, only seven million Mt had been produced, 14.85 million Mt CO_2e could have been avoided.[269]

Another USEPA study compared the climate change benefits of different waste management methods, including waste prevention, recycling, composting, incineration, and landfilling, through an investigation of 16 types of waste materials, including three types of plastic (HDPE, LDPE, and PET).[270] Waste prevention showed the biggest climate benefits, with 18 million Mt of CO_2e reduction if waste generation dropped to 1990 levels. The study also concluded that source reduction and recycling result in negative net greenhouse gas emissions, while combustion adds to the climate burden by increasing emissions.[271]

It is important to note that source reduction often refers not only to replacing plastic packaging with reusable and refill-friendly alternatives, but also to substituting plastic with other materials to serve the same function. While the former addresses the root causes of the current waste crisis, the latter continues the reliance on disposable items, lightweight plastic, and bioplastic. Continued use of single-use products that are outside a closed-loop system for their end-of-life phase perpetuates a linear, throw-away economy by providing the means to sustain current production and consumption patterns and undermining the transformation needed in plastic production and consumption systems as a whole. In this regard, effective strategies for plastic source reduction are those that use reusable and refill-friendly alternatives in order to avoid waste generation in the first place.

Phase Out Waste Incineration

As this chapter suggests, incineration is the primary source of greenhouse gas emissions from the management of plastic waste. As reliance on incineration grows, so do emissions from plastic waste. Even when waste incinerators generate electricity that might otherwise have been generated by burning natural gas, incineration still consumes more energy, resulting in greater greenhouse gas emissions compared to other management options.[272] Moreover, the offset greenhouse gas emissions will decrease over time as fossil fuels for electricity generation are phased out. As this energy mix shifts to incorporate more renewable sources, using plastic incineration for energy production will become a much greater percentage of net CO_2 emissions from the energy sector.[273]

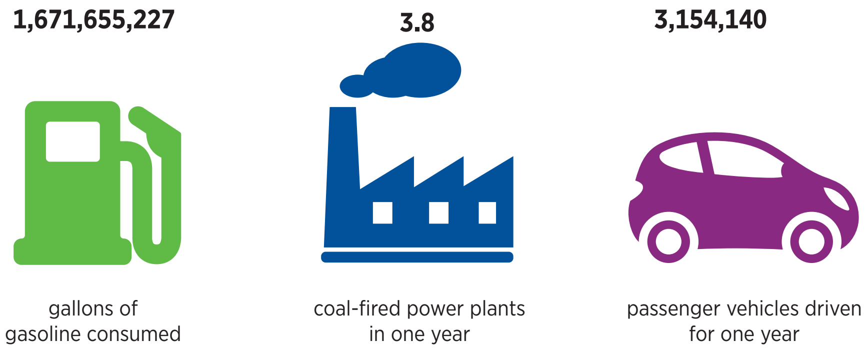
In Europe, the total greenhouse gas emissions from plastic—estimated at 132 Mt in 2017—and an additional 90 Mt of CO_2 will be released each year based on the current trend of increased incineration in the region.[274] This projection highlights the urgent need to end the use of incineration as a waste management strategy. This conclusion runs counter to the dangerous trend of new and expanded investments in incineration in Asia, Latin America, and Africa.

The climate impacts of using waste-to-energy incineration for municipal solid waste do not end with increased greenhouse gas emissions from the incineration of plastic. In municipal solid waste incinerators, mixed plastic is treated with food waste that is high in water content, resulting in energy loss and thus higher greenhouse gas emissions.[275] Waste incineration also has many other drawbacks. Evidence demonstrates significant acute and residual environmental health risks related to incineration. High construction and maintenance costs leave nearby communities indebted. Incinerators experience a lock-in effect, creating a constant demand for feedstock for facilities to stay operational. Significantly, incineration facilities are disproportionately located near communities of color and low-income and marginalized communities. Experience demonstrates that such communities often lack both the necessary resources and meaningful opportunities to challenge these siting decisions, even when the projects involved are likely to negatively impact their environment and health.[276]

Increasingly, policy directives are acknowledging the dangers of waste incineration. In 2017, the European Commission released a communication on the role of WTE in the circular economy that recommended introducing measures to phase out landfilling and other forms of residual waste treatment, including incineration, pyrolysis, gasification, and plasma processes.[277] It also recommended providing economic incentives and co-financing for waste prevention, reuse, and recycling performance. Similarly, the New Plastics Economy Global Commitment explicitly excludes waste incineration by stating, "No plastic should

FIGURE 15

Annual Greenhouse Gas Benefit of 50% Source Reduction of Plastic Packaging Products in MSW in 2006

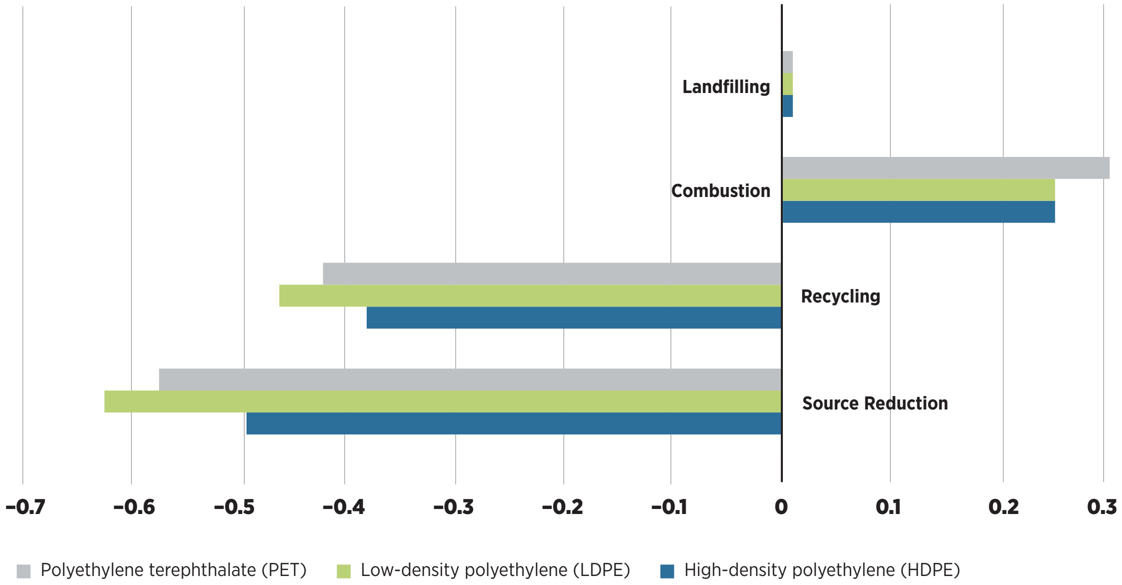


Greenhouse gas impact of 50% source reduction in the US = 14,856,000 Mt CO_2e saved

Source: U.S. EPA (2009). Opportunities to Reduce Greenhouse Gas Emissions through Materials and Land Management Practices. *https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator*.

FIGURE 16

Net Greenhouse Gas Emissions from Source Reduction and MSW Management Options



Unit: Mt CO_2e/ton

Source: U.S. EPA (2006). *Solid Waste Management and Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks Report.* Third edition.

end up in the environment. Landfill, incineration, and waste-to-energy are not part of the circular economy target state."[278] In 2017, 250 mayors across the United States unanimously agreed to a resolution on transitioning to 100 percent renewable energy, affirming that waste-to-energy must not be classified nor subsidized as a renewable energy.[279] At a global level, the C40 Cities' Advancing Towards Zero Waste Declaration is another good example of cities pledging to tackle the waste crisis at the source, by reducing municipal solid waste generation per capita by at least 15 percent by 2030 compared to 2015, reducing the amount of municipal solid waste disposed to landfill and incineration by at least 50 percent on the same timeline, and increasing the diversion rate away from landfill and incineration to at least 70 percent.[280]

Maximize Reuse and Recyclability for Other Waste Streams

In addition to calling for an end to incineration and the elimination of single-use plastic packaging, zero waste has the added benefit of identifying the best use for all waste streams, not just plastic. This is achieved by careful separation of waste streams at the source, such as a household or business. Separated streams of food waste and other organic compounds can be used for composting or anaerobic digestion, which can lower greenhouse gas emissions from biogenic waste by diverting it from landfills.[281] Non-organic waste streams have considerable value when recycled, reused, or otherwise redeployed back into a circular economy, and such measures can further reduce greenhouse gas emissions by reducing the need for extracting virgin materials. The elimination of single-use plastic packaging augments recycling efforts by increasing the quality of recycled waste streams, which are currently contaminated with unrecyclable plastic waste. In addition, contaminated mixed waste creates the perception of a much greater stream of residual waste than actually exists, thereby artificially increasing the perceived demand for industrial-scale waste management solutions like incineration.

In addition to calling for an end to incineration and the elimination of single-use plastic packaging, zero waste has the added benefit of identifying the best use for all waste streams, not just plastic. This is achieved by careful separation of waste streams at the source, such as a household or business.

CHAPTER SEVEN

Plastic in the Environment

As the preceding chapter suggests, the greenhouse gas impacts of plastic do not stop when plastic is discarded. For the majority of all plastic ever made, its use and disposal is only the first and shortest phase of a lifecycle that will span centuries or more. Notwithstanding the significant role of plastic in the global economy, in global waste streams, and to the global climate, this report demonstrates that climate impacts from the plastic lifecycle remain poorly quantified and poorly understood. The least studied and, as yet, least understood of these impacts arise once plastic has been released into the environment, starting as pre- and post-consumer waste contaminating urban streets, farmlands, landfills, natural areas, coastal zones, and waterways, and making their way via freshwater rivers and streams to the ocean.

The relatively modest amount of climate-relevant research to date has focused primarily on the impacts of plastic and microplastic within oceanic environments and aquatic ecosystems. This chapter provides a brief introduction to that research. It briefly reviews emerging evidence of the various pathways through which climate impacts are or may be occurring. It acknowledges the significant data gaps and uncertainties with respect to those pathways. Lastly, it highlights the potentially profound risks should those gaps remain unfilled.

PLASTIC IN THE OCEAN

Until recently, the science of plastic pollution in the ocean has focused on its global abundance, distribution, and evidence of ecological harm. Anecdotal reports of plastic being ingested by sea turtles appeared soon after plastic production began expanding in the 1950s, and by the 1960s, researchers had documented plastic in the stomachs of sea birds.[282] Significant amounts of plastic debris were also reported in the proceedings of a workshop on oil pollution convened by the US National Academy of Sciences in 1973, including reports that plastic debris was aggregating other toxics and being routinely ingested by ocean wildlife.[283] A second workshop held the same year on potential ocean pollutants identified similar concerns with the potential impacts of plastic in the environment.[284]

A team led by Sarah-Jeanne Royer of the University of Hawaii released a study documenting that the growing volume of plastic accumulating in the environment may be contributing to climate change.

The first targeted research into the environmental impacts of ocean plastic began in 1972 when EJ Carpenter and KL Smith documented plastic floating on the Sargasso Sea surface.[285] By the early 1980s, the issue began to attract growing attention and more targeted research.[286]

To date, research on marine plastic pollution has reached three main conclusions. First, plastic breaks into smaller pieces that can now be found in the most far-flung corners of the globe, including the deepest area of the ocean. Second, attached to these plastic pieces are a mix of toxic chemicals that are harmful to humans and animals, known as persistent organic pollutants. Third, and finally, plastic harms aquatic animals through entanglement and ingestion at all levels of the food chain, and humans in turn ingest plastic through a variety of pathways.[287]

In August 2018, a team led by Sarah-Jeanne Royer of the University of Hawaii released a study documenting that the growing volume of plastic

Opposite: © Sarah-Jeanne Royer

accumulating in the environment may be contributing to climate change.[288] These impacts are a result of the exposure of plastic to solar radiation and the slow breakdown, or degradation, of plastic in the environment.

> The degradation and breakdown of plastic represents a previously unrecognized source of greenhouse gases that are expected to increase, especially as more plastic is produced and accumulates in the environment.

Plastic degradation induces a chemical change that reduces the molecular weight of the polymer.[289] Degradation begins from the moment plastic is exposed to ambient conditions. With time, the polymer weakens and often becomes brittle, breaking down into smaller particles. In the ocean, weathering processes such as biodegradation, thermo-oxidative degradation, thermal degradation, hydrolysis, and solar radiation contribute to this breakdown.[290] Plastic photodegradation (exposure to light) is of particular interest to this report because it triggers the production of greenhouse gases.[291] This unexpected discovery shows that the degradation and breakdown of plastic represents a previously unrecognized source of greenhouse gases that are expected to increase, especially as more plastic is produced and accumulated in the environment.

Royer's study also revealed that among the common types of plastic used worldwide, low-density polyethylene, the most prevalent plastic discarded in the ocean today, releases methane, ethylene (C_2H_4), ethane, and propylene at the highest rate. The results further showed that, as the surface area of plastic increases due to weathering and breakdown in the ocean, there is a tremendous increase in methane and ethylene off-gassing. For example, LDPE powder off-gases methane 488 times more rapidly than when the same weight of LDPE is in pellet form. Finally, the study demonstrated that plastic exposed directly to sunlight (not submerged in water) produces even more of the gases. LDPE releases approximately two times more methane and 76 times more ethylene when exposed to air than when incubated in water. This indicates that the plastic in oceans and terrestrial environments contributes to the greenhouse gas impacts of the plastic lifecycle, though it is often overlooked. The results even indicate that, once initiated, the production of hydrocarbon gases continues in the absence of sunlight. While the quantity of emissions of individual plastic particles is small, these emissions continue indefinitely as the plastic continues to break down, exposing yet more surface area to reactive processes. These emissions will continue to grow as the volume of plastic in the oceans and in the terrestrial environment increases.[292]

Another potential indirect greenhouse gas effect of ocean plastic has only recently begun to emerge in the scientific literature. While the data remain too preliminary to draw broad conclusions, that research is presented here to explore the potential impact plastic may have on the health of planktonic organisms that form the foundation of oceanic food chains. These planktonic communities, made up of phytoplankton and zooplankton, also play an essential role in the ocean's carbon cycle, capturing carbon dioxide at the surface and transporting the carbon to the deep oceans, where it is sequestered away from the atmosphere for centuries. As discussed fully below, there is growing evidence that these plankton—like other marine species—are ingesting ever greater quantities of microplastic debris with potentially significant impacts on their metabolism, reproductive success, and mortality rates.[293] This raises significant questions about the impact that microplastics may have on the ocean's ability to store and absorb atmospheric CO_2 and other greenhouse gases. Earth's oceans provide the largest single natural sink for anthropogenic greenhouse gases, in the absence of which the climate impacts of fossil fuel combustion would be significantly greater. Since the industrial era, the oceans have absorbed 30-50 percent of atmospheric anthropogenic CO_2.[294] Disruptions to the ocean's ability to absorb CO_2 could have a massive impact on increased atmospheric buildup of CO_2 and other harmful gases that had been previously absorbed by phytoplankton.

GREENHOUSE GAS EMISSIONS FROM PLASTIC: HAWAII CASE STUDY

The study by Royer et al. was the first to examine greenhouse gas emissions from plastic under natural conditions in oceanic and terrestrial environments, and it tested some of the most commonly used types of plastic, such as PP, PS, HDPE, and LDPE from both virgin plastic and ocean plastic sources.[295] The experiments detected ongoing emissions of methane and ethylene.

In stations set up on the roof of the laboratory facility, Royer's team conducted two long-term experiments incubating virgin LDPE and aged LDPE collected from Station ALOHA in the North Pacific Subtropical Gyre. Plastic was exposed to ambient sunlight in extremely pure water for several months to measure hydrocarbon off-gassing. Both aged plastic collected at the sea surface and virgin plastic were tested to determine their emissions rates for a period of 212 days and 152 days, respectively. Other experiments also evaluated the effect of plastic density and fragment morphology (pellets, flakes, and powder) on the production of greenhouse gases. Finally, the study tested how differences in the medium, either air or water, affected greenhouse gas emissions.[296]

Royer et al. discovered that exposure to ambient sunlight caused the seven most commonly used kinds of plastic to produce measurable amounts of both methane and ethylene. Methane emissions ranged from 10-4100 pmol per gram per day. Ethylene emissions ranged from approximately 20–5100 pmol per gram per day.[297] Royer suggests that the higher rate of off-gassing from LDPE, which is incorporated in a wide variety of plastic products including plastic bags, shrink wraps and films, plastic coatings for paper milk cartons and beverage cups, container lids, and squeezable bottles for soaps, shampoos, and condiments, among many other uses, may be due to its weak polymer structure and more exposed hydrocarbon branches.

Virgin vs. Aged Plastic

Before they are reshaped into bottles, bags, and other plastic products, plastic resins are produced and transported as virgin plastic pellets, also known as nurdles. These pellets can and do escape into the environment from sewer drains and discharge pipes at plastic plants, from leakage and spills from trucks and rail cars transporting virgin pellets, and from cargo vessels and containers that transport virgin plastic around the world. They are among the most common forms of

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plastic pollution worldwide. In Royer's experiments, greenhouse gas emissions from these virgin plastic pellets increased over time while aged-plastic emissions remained constant. With the exception of methane, emissions of greenhouse gases from virgin plastic pellets were higher than emissions from aged plastic. This is likely due to the presence of ultra-violet (UV)-resistant plasticizers that are often added to plastic products to counteract the effects of UV radiation and slow down the degradation processes, and are not found in virgin plastic.[298]

Physical Features

The morphology of plastic also affected the degree to which it emitted greenhouse gases. As plastic cracks, fractures, and breaks, the surface area increases, increasing the total surface available for photodegradation. The production rates of greenhouse gases increase progressively as the plastic breaks down into smaller and smaller pieces with greater surface area. Royer et al. discovered that as the surface area of plastic increases due to weathering and degradation in the ocean, more and more greenhouse gases will be produced for the same amount of plastic over time.[299]

Royer et al. also found that both virgin and aged plastic continue to emit greenhouse gases to the environment (both in air and submerged in seawater) for an undetermined and potentially indefinite period. This could be attributed to photodegradation fragmenting plastic into progressively smaller fragments, microplastic (less than 5 mm) and nanoplastic[300] (less than 100 nm). Moreover, and as discussed further below, the continuous decline in the size of plastic particles makes them more easily absorbed or ingested by even smaller organisms, thus increasing their bioavailability and potential impact across ecosystems.

ESTIMATING DIRECT GREENHOUSE GAS EMISSIONS FROM OCEAN PLASTIC

Building on the emissions rates found by Royer et al. for LDPE and other plastic resins, it is feasible to produce a very preliminary estimate of the annual rate of greenhouse gas emissions from ocean plastic using a standing stock of sea surface microplastic[301] and the emissions rate of LDPE powder.[302] As discussed fully below, this estimate has significant limitations and uncertainties. Accordingly, it is presented here for discussion purposes but is not incorporated into the global estimates of lifecycle emissions presented elsewhere in this report.

The first global estimate of microplastic found at the sea surface was published in 2014 by 5Gyres, in which Eriksen et al. estimated that 5.25 trillion microplastic particles, equivalent to 66,100 Mt of particles, were floating at the sea surface.[303] However, standardized prediction models of global mass estimates done by Erik van Sebille et al. in 2015 estimated that the amount of small floating microplastic debris is substantially greater than previously published.[304] Estimates showed that the standing stock of microplastic concentrated at the sea surface in 2014 ranged from 15 to 51 trillion particles, weighing between 93,000–236,000 Mt.[305] Significantly, this estimate was equivalent to just one percent of the global plastic waste estimated to enter the oceans in the year 2010 alone, and a far smaller fraction of the plastic discharged into the oceans over the past seven decades. Two other standing stock estimates were calculated in the same study. The total microplastic count and mass patterns were similar across all three models, with higher amounts in the subtropical regions and lower amounts in the tropical and high-latitude regions.

According to Royer et al., the highest gas-producing plastic (LPDE in powder format) produced methane at a rate of 55 nmol per gram per day.[306] Using the estimated 236,000 Mt of standing stock of sea surface microplastic pollution from the 2015 van Sebille model, there is an annual emissions rate of 4.74 x 1015 nmol per year. This totals an annual methane production of 76 Mt from the standing stock of plastic at the sea surface. Applying the 100-year global warming potential of methane yields annual greenhouse gas emissions of 2,129 Mt CO_2e.

Royer et al. also determined a rate for ethylene in LDPE powder form.[307] Doing the same calculation for ethylene equates to 51 Mt of annual ethylene production.

Given the challenges mentioned above for the collection of data on greenhouse gas emissions rates for all ocean plastic, preliminary estimates for both methane and ethylene emissions assume that both the rate and amount at which plastic is input into the ocean remains constant. With a 33-36 percent predicted increase in plastic production by 2025, the amount of methane emissions produced from sea surface ocean plastic would be 101-103 Mt per year if no mitigation efforts were implemented to stop leakage from land. For ethylene, this would amount to 68–70 Mt per year.

It is important to note the multiple and significant limitations of these estimates. For example, these estimates are based on Royer et al. emissions rates for methane and ethylene for microplastic particles exposed to UV radiation at the sea surface in a tropical environment. Thus, they do not encompass all possible emissions rates for plastic slightly submerged in the water column and for different levels of plastic degradation. In addition, these calculations only consider the highest hydrocarbon-gas-producing plastic type, LDPE in powder form, to represent the entire floating microplastic debris standing stock, since polyethylene accounts for most of the plastic found in the environment.[308] Van Sebille's 2015 global stock estimate of 236,000 Mt does not evaluate the standing stock of plastic by resin type.

There is still a considerable amount that is not known about the greenhouse gas emissions of plastic in the environment. The fact that the age and treatment of plastic are typically unknown at the time of collection also affects emissions estimates. Annual estimates only consider the tiny fraction of ocean plastic found at the surface and do not consider emissions from the "missing plastic" in the water column, on the seafloor, stranded on coastlines, or in larger debris, like fishing gear. Van Sebille et al. highlight the difference between annual inputs, which are calculated based on all plastic types, and standing stock estimates, which are based on sea surface microplastic, mostly PP and PE.[309]

> There is still a considerable amount that is not known about the greenhouse gas emissions of plastic in the environment. Annual estimates only consider the tiny fraction of ocean plastic found at the surface and do not consider emissions from the "missing plastic" in the water column, on the seafloor, stranded on coastlines, or in larger debris, like fishing gear.

Another missing variable involves ocean plastic removal rates, which are not yet fully understood[310] and can skew emissions rate estimates. Stranding and eventual sinking of floating plastic likely accounts for the bulk of surface removal. Also, ingestion by animals, transportation to land and regurgitation, and fecal pellets sinking to the seafloor[311] may also skew estimated emissions rates.

Finally, and more significantly from the perspective of assessing the global impacts of plastic pollution, Royer et al. conclude that more gases are emitted by plastic when it is exposed to air than when it is in submerged in water. LDPE plastic produced 76 times more ethylene and 2.3 times more methane in air than in water. The difference in emissions rates for plastic in water compared to plastic exposed to air is partly due to temperature and heat buildup, resulting in the plastic material reaching a temperature higher than the surrounding medium.[312] This suggests the need for additional research into the scale of emissions from plastic exposed to greater ambient temperatures—including not only plastic floating on the surface, but the massive quantities of plastic accumulated on coastlines, beaches, and riverbanks, as well as the still poorly estimated quantities of plastic disintegrating in terrestrial environments around the world. Any estimation of the greenhouse gas impact of plastic waste must ultimately take into account not only the immense volume of plastic pollution found worldwide, but the diverse environments in which that plastic pollution occurs.

Compared to the millions of tons of emissions from other links in the plastic lifecycle, and the billions of tons in which the global carbon budget is measured, the methane production rates calculated by Royer et al. may appear comparatively modest. Royer's team drew a similar conclusion, at least with respect to methane.[313] As Royer observed, however, as plastic production increases and the volumes of mismanaged waste entering oceans increases,[314] methane emissions from degrading plastic will likely also increase and may warrant increased concern. Future studies are needed to address the role of plastic off-gassing methane, ethylene, and other greenhouse gases.

POTENTIAL IMPACT OF MICROPLASTIC ON THE OCEANIC CARBON SINK

The preceding discussion addresses the direct emissions of greenhouse gases from oceanic plastic pollution. In addition to these direct climate impacts, emerging but still preliminary evidence suggests that plastic pollution may be having a less direct but ultimately greater role in climate change through its impact on the species that form the foundation of oceanic food chains and provide the biological carbon pump that sequesters carbon in the deep oceans.

> The impacts of ocean plastic on ecosystems that are directly responsible for the ocean's CO_2 gas exchange cycle may be indirectly causing more atmospheric greenhouse gas emissions.

The world's oceans provide the largest natural sink for anthropogenic greenhouse gases. Since the dawn of the industrial era in the late 18th century, the oceans have absorbed 30–50 percent of atmospheric anthropogenic CO_2.[315] The impacts of ocean plastic on ecosystems that are directly responsible for the ocean's CO_2 gas exchange cycle may be indirectly causing more atmospheric greenhouse gas emissions.

These impacts may occur through four distinct but interconnected pathways. First, emerging evidence indicates that microplastic particles can affect the phytoplankton whose photosynthesis absorbs (or "fixes") nearly half of the CO_2 that is released into the earth's atmosphere.[316] Oceanic primary production (the first step in the food chain) accounts for up to 80 percent of the planet's total oxygen production.[317] Phytoplankton are the ocean's main primary producers, taking CO_2 from the atmosphere and water from the ocean and using photosynthesis to produce carbohydrates, but laboratory experiments have shown that microplastic exposure can be toxic to phytoplankton. The smaller the microplastic size, the greater its toxicity.[318] A study released in 2018 found that this toxicity is able to disrupt phytoplankton feeding, reproduction, physical ingestion, and metabolism, among other impacts. In one laboratory study, microplastic reduced the rates of photosynthesis of contaminated phytoplankton by 45 percent.[319] These impacts have real-world implications beyond the laboratory. Research demonstrates that phytoplankton readily integrate with and form aggregates with microplastic particles when they are present in water.[320] It is thus possible that ocean plastic is affecting the metabolism, survival, and reproduction of the organisms responsible for the base of oceanic food chains, and indirectly influencing the ocean-atmosphere gas exchange process. However, more studies are needed to determine how exactly plastic affects the ocean's biological carbon pump through primary production.

Plastic not only affects the phytoplankton cells that absorb CO_2 from the ocean's surface, but it may also be harming the zooplankton (microscopic animals) that transport that carbon to the deep oceans. Just as phytoplankton are the primary fixers of carbon in ocean ecosystems, zooplankton are the first and most important consumers of phytoplankton. More importantly from the climate perspective, zooplankton are instrumental in taking the carbon fixed by the phytoplankton and transporting it to the deep ocean in the form of fecal pellets. Without this critical step in the process, the CO_2 fixed by the phytoplankton would quickly re-enter the surface waters and the atmosphere.

Changes to this segment of the food chain (phytoplankton and zooplankton) may thus affect the ocean's ability to absorb and store CO_2. Figure 17 illustrates the role of plankton in carbon transportation between the atmosphere and the ocean.

Copepods are the most common types of zooplankton. The copepod Calanus helgolandicus is a keystone species in Europe and the Northeast Atlantic, making up 90 percent of all mesozooplankton biomass.[321] In a 2015 study led by Matthew Cole of Plymouth Marine Laboratories, researchers demonstrated that microplastic exposure negatively affected the metabolism and health of copepods in at least three distinct ways. First, copepods that ingested plastic reduced

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their feeding rates by 40 percent. Second, with exposure to microplastic over time, copepod eggs became smaller and were less likely to hatch. Third, exposure to microplastic increased overall mortality among contaminated copepods.[322] As a result, Cole et al. concluded that, over time, growing exposures to microplastic could lead to significant reductions in the amount of carbon biomass ingested by zooplankton.[323] Put more simply, zooplankton might ingest less and less of the anthropogenic carbon being fixed by the ocean's phytoplankton—even as those phytoplankton themselves are fixing carbon less efficiently because of exposure to toxic microplastic.

While the research by Cole et al. focused on the North Atlantic Ocean, the ingestion of plastic by zooplankton is a global phenomenon. A 2015 study in the Northeastern Pacific Ocean off the Pacific coast of North America found microplastic was ingested by both copepods and euphasids, indicating that even species at the lowest levels of the oceans' food chain were mistaking plastic for food.[324] A separate study published in 2016 by researchers with the Ocean University of China reached similar results, finding that microplastic affected both the growth of microalgae and the efficiency of photosynthesis.[325] Sampling conducted in the Baltic Sea found microplastic ingestion by every taxon of zooplankton studied, including mysid shrimp, copepods, rotiferans, and polychaete worm larvae, among others.[326] It also demonstrated that microplastic can be transferred from smaller to larger zooplankton when bigger plankton species eat smaller ones. The ingestion of microplastic has also been documented for multiple taxa of zooplankton in the Indian Ocean off the coast of Kenya,[327] and in 11 separate zooplankton taxa in the Yellow Sea off the coast of China.[328]

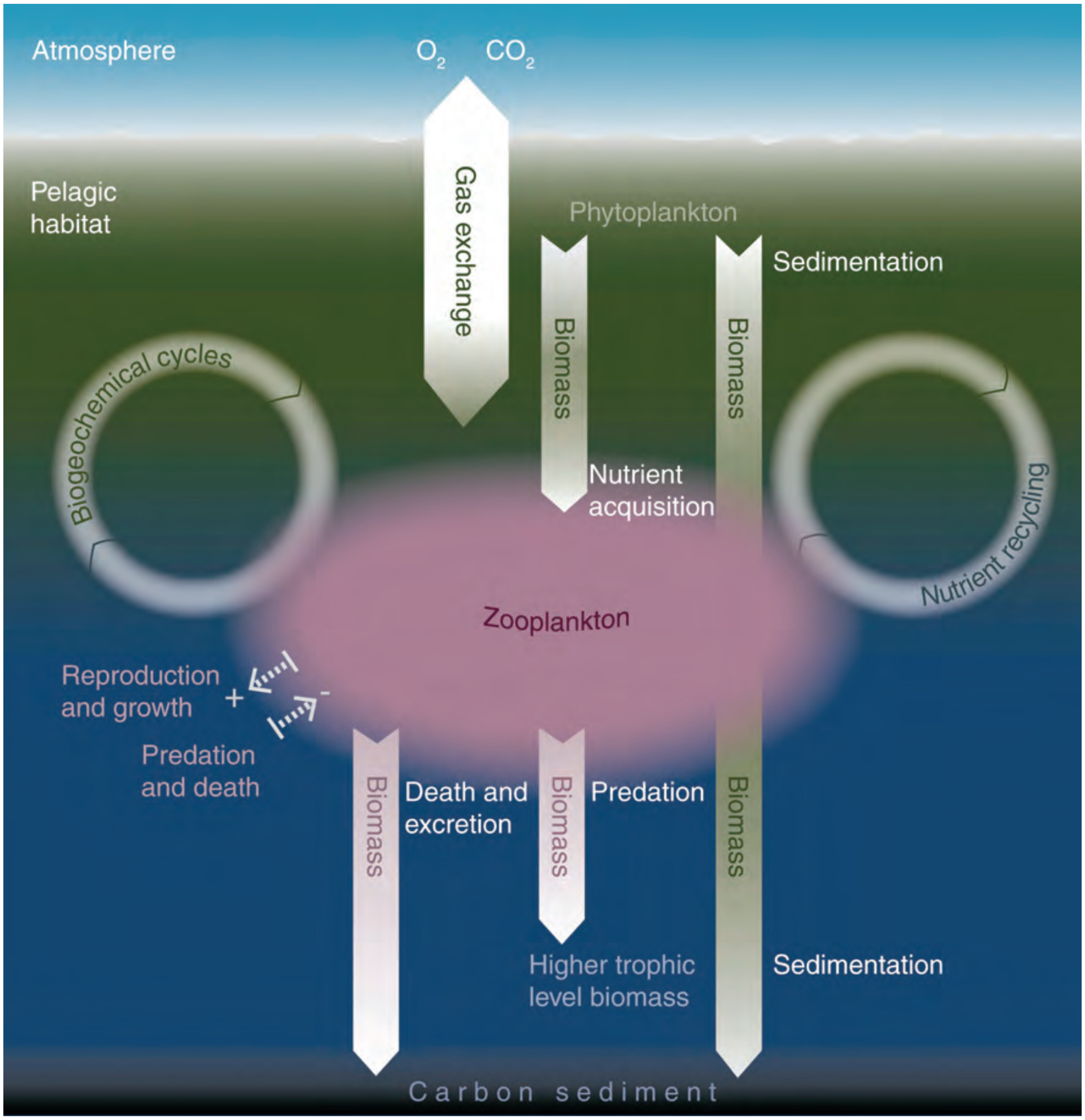
It is likely that microplastic affects the many and varied taxa of zooplankton in different ways, and that some taxa will be less affected than others. For example, a study of the Pacific Oyster, Crassostrea gigas, did not find any impacts to its development or feeding capacity from exposure to polystyrene microplastic.[329] Clearly, additional research is needed to understand the potential scale and scope of the problem. Given the critical importance of the ocean carbon sink to the global climate, however, the potential of microplastic pollution to affect both the fixing of CO_2 by phytoplankton and its transport to the deep ocean by zooplankton should be a cause of significant concern and immediate and significant research.

This raises a third route through which microplastic has the potential to affect the ocean's biological carbon pump. When zooplankton ingest phytoplankton, the carbon they absorb is then transported to the deep ocean in fecal pellets—a major constituent of marine snow. The fecal pellets slowly descend to deep water, where they are deposited in the muck on the ocean floor. Studies have documented that microplastic is transported below the surface in zooplankton fecal pellets.[330] However, when fecal pellets are contaminated by microplastic, they sink more slowly and break up more readily than uncontaminated pellets,[331] thus reducing the proportion of the carbon that reaches the deep sea to be sequestered.

Fourth, and finally, it is important to consider the fate and impact of the plastic that does reach the deep sea. The sea surface is not the end point for plastic in the oceans. Sea surface estimates only account for approximately one percent of the estimated millions of Mt of plastic waste created on land.[332] These low estimates have led scientists to explore plastic sinking mechanisms.[333] Plastic's

FIGURE 17

Carbon Transportation Processes Between Phytoplankton and Zooplankton



Source: Andrew Brierley, *Plankton*, 27 Current Biology R478 (2017), *https://www.sciencedirect.com/science/article/piiS0960982217302154*. Image by Steve Smart.

ability to sink relates to its density (if greater than water) and biofouling (accumulative buildup of organic matter and organisms).[334] For example, microplastic sticks to algal species (phytoplankton aggregates) that travel down into the water column, which may partially explain why the sea floor has become a major sink for microplastic.[335] The presence of microplastic on the sea floor may also be affecting the ocean's carbon stocks.[336] Their behavior and impact in deep ocean environments remains largely unknown.

REDUCING THE CLIMATE IMPACT OF PLASTIC IN THE ENVIRONMENT

As the research by Royer et al. suggests, the sources and scale of climate impacts from plastic in the environment are only beginning to be identified and investigated. Technological improvements in satellites, hyperspectral imagery, and drones can help provide better estimates of all ocean plastic greenhouse gas emissions, especially those carried back to shorelines and on land.[337] Terrestrial sources of plastic waste and ocean plastic returned to land are likely bigger emitters since they are exposed to more ambient conditions (sunlight and air) and thermal loading that exacerbates greenhouse gas release.

If waste management is not improved by 2025, plastic inputs into the ocean will increase by an order of magnitude,[338] regardless of the increased production rate. Irrespective of improvements to waste management, the problem of greenhouse gas emissions from the plastic lifecycle cannot be solved downstream. For example, recycling ocean plastic is not a viable solution to plastic-related greenhouse emissions or to pervasive and growing plastic pollution throughout the environment. A recent study looked at the recyclability of four types of plastic after being exposed to UV radiation in the ocean. All plastic types in this study presented damage to their thermal and mechanical properties, making mechanical recycling unfeasible.[339]

Reducing sources of plastic entering the oceans and waterways must be an urgent area of focus. Rivers are one entry point (1.15-2.41 million Mt per year); most of the top 20 most polluted rivers are located in Asia and represented 67 percent of this rate.[340] It must be stressed that the transportation of ocean plastic via river systems remains largely understudied, and further monitoring of plastic pollution is required. Studies looking at how, where, and what type of plastic pollution is entering these rivers are needed.

Yet these solutions address the plastic problem only after the plastic has been created, disposed of, and turned into waste. Unless the growth of plastic production and disposal is reversed, such end-of-life efforts to manage plastic will be confronted with ever greater flows of pollution to be managed. The most effective way to stem this rising tide of plastic in the environment is to dramatically reduce the amount of plastic being produced and discarded.

Shifting to a circular economy from the current linear economy can introduce potential solutions to the plastic pollution problem in all types of environments, including oceanic and terrestrial environments. Where circularity isn't possible, replacement with natural-based products for plastic can help. However, bioplastic is not necessarily biodegradable (see Box 3). 5Gyres' Better Alternatives Now (BAN List) 2.0 demonstrated how some products are only biodegradable in industrial systems and not in natural environments.

> Plastic reduction and reuse, part of zero-waste living, is a growing trend worldwide. Ending the production of new plastic is the most reliable way to reduce the generation of microplastic in general.

There is also a need to improve product design and packaging to aid the recovery of plastic. This can occur by implementing extended producer responsibility, making producers legally and financially responsible for their products' environmental impacts.[341] However, improvements to economic models and logistical aspects of extended producer responsibility are still needed.

Scaling zero-waste strategies is the solution that best leads to a circular economy. Plastic reduction and reuse, part of zero-waste living, is a growing trend worldwide and, in some cases, is helping remove ocean plastic pollution. For example, lost or discarded fishing gear is being transformed—or upcycled—into sunglasses and skateboards. Ending the production of new plastic is the most reliable way to reduce the generation of microplastic in general.[342] Collectively, all these steps reduce the leakage of plastic into both terrestrial and aquatic environments, which is the most efficient way to reduce microplastic in the environment and prevent its associated greenhouse gas emissions.


GREENPEACE

CHAPTER EIGHT

Findings and Recommendations

PLASTIC & CUMULATIVE GREENHOUSE GAS EMISSIONS

The cumulative emissions from the plastic lifecycle illustrate the degree to which increased plastic production is inconsistent with the immediate need to rapidly reduce global greenhouse gas emissions. Moreover, the inherent difficulty of constructing an emissions profile for the lifecycle of plastic helps explain why this massive and growing source of greenhouse gas emissions has remained overlooked.

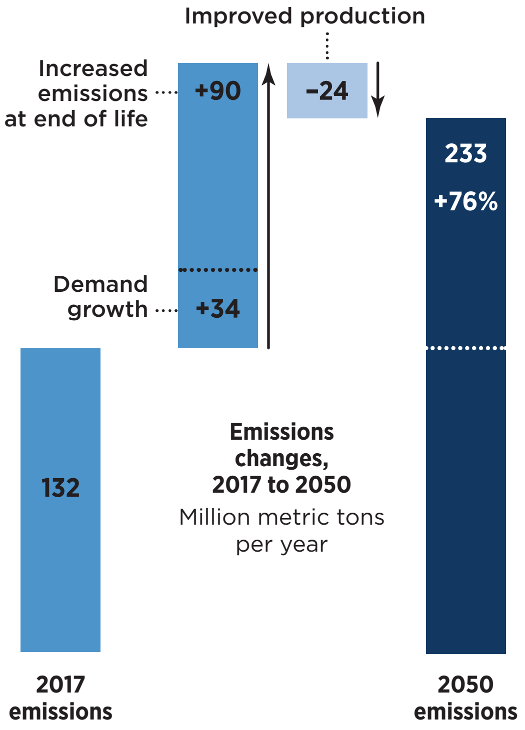
As made clear in the Extraction & Transport and Production & Manufacture chapters of this report, developing estimates of the greenhouse gas emissions intensity of plastic production is extremely challenging. The myriad sources of emissions, and the diversity in emissions intensity of such sources, significantly limits what bottom-up approaches using publicly available information can include. The bottom-up approach of identifying major sources is important both to demonstrate the sheer variety of emissions sources and to highlight the challenges in addressing this industry holistically. Because of these limitations, existing emissions estimates of the plastic production process are likely to undercount or omit sources of emissions, and these should be understood as minimum estimates.

Using existing cradle-to-resin emissions estimates and industry's growth rate projections, this report calculated several potential scenarios for cumulative emissions from plastic production. At current rates of emissions intensity, cumulative emissions over the period 2015–2050 from cradle-to-resin plastic production are likely to be at least 52 gigatons CO_2e. Even full incorporation of renewable energy in the production process would only reduce emission intensity by about half, and there are major emissions to such decarbonization.

FIGURE 18

Growth in Net CO_2 Emissions from Plastic in the EU

Material Economics found that emissions from plastic could grow significantly by 2050, largely due to increased emissions at the end of the plastic lifecycle and demand growth.



Source: Material Economics, The Circular Economy (2018).

Management of plastic waste is also a significant source of emissions, especially from waste-to-energy incineration and open burning. If industry plans for growth in both plastic production and the role of incineration in plastic waste management materialize, cumulative net emissions from

Opposite: © Tim Aubry/Greenpeace

incineration from 2015 to 2050 are likely to contribute at least an additional four gigatons of CO_2e. Notably, these are net emissions, assuming that energy from waste incinerators replaces other energy sources, including fossil energy. This figure only accounts for incineration of plastic packaging, about which the most is understood. If management of other kinds of plastic leads to a greater reliance on incineration, emissions from these sources will grow. This projection does not include the large but unmonitored emissions from open burning.

In 2019, the production and incineration of plastic will add an estimated 859 million metric tons of greenhouse gases to the atmosphere—equal to the emissions from 189 five-hundred-megawatt coal plants.

Projecting beyond 2050 is difficult, particularly in light of the need to reach net zero emissions by that year, but even conservative estimates are alarming. As noted earlier in this report, even assuming no growth in plastic production from 2050 to 2100 and full integration of renewable energy into industrial processes for plastic production, cumulative emissions reach 59.5 gigatons of CO_2e. Similarly, assuming no growth in the scale or net emissions intensity of incineration for the second half of the century, emissions from waste-to-energy processes would add an additional 15.4 gigatons of CO_2e.

These estimates are deliberately low. If growth in plastic production and incineration is allowed to continue apace through 2050, there is no reason to believe it will simply halt thereafter. Rather, these explicitly conservative estimates should be understood as demonstrations of the scale and severity of the potential future climate impact of the plastic lifecycle.

Finally, for plastic that makes its way into oceans, rivers, soils, and other destinations in the environment, emissions and other climate impacts continue to mount via off-gassing and interference with marine food webs. Although quantifiable emissions at this stage in the lifecycle appear small at present, the degree to which these emissions contribute to atmospheric greenhouse gas concentrations, and the rate at which they will grow as plastic continues to accumulate and degrade in the environment, is still unknown. Plastic degrading in the ocean presents yet another little studied but potentially catastrophic source of climate impacts if contamination by microplastic reduces the ability of plankton to absorb CO_2 and transport it to the ocean depths. As with all other stages in the plastic lifecycle, the continued growth in plastic production only exacerbates these risks.

In 2019, the production and incineration of plastics will add an estimated 859 million metric tons of greenhouse gases to the atmosphere—equal to the emissions from 189 five-hundred-megawatt coal plants. With the petrochemical and plastic industries planning a massive expansion in production, plastic will emit over 56 billion metric tons of carbon-dioxide-equivalent greenhouse gases between 2015 and 2050, 10–13 percent of the entire remaining carbon budget.

The foregoing summation of emissions from the plastic lifecycle points to a single conclusion: plastic itself is the problem. Decarbonization can only partially reduce emissions from the plastic production process. Ironically, as the energy grid shifts toward greater reliance on renewable energy, the net greenhouse gas impact of plastic incineration grows. Finally, plastic in the environment further contributes to accumulating greenhouse gases simply because of its fundamental chemical and physical nature. Because plastic itself is the problem, the most effective way to reduce the greenhouse gas emissions from the plastic lifecycle is to produce less plastic.

Lifecycle Plastic Emissions Relative to Mitigation Scenarios and Carbon Budget Targets

IEA, Carbon Tracker, and the IPCC are among several organizations that have developed methodologies for measuring greenhouse gas emissions and proposed pathways for emissions reductions. Despite differences in approach, each models the likelihood of reaching climate stabilization targets of 2°C and 1.5°C under certain scenarios and provides a point of reference for analyzing the emissions from the plastic lifecycle.[343]

Current emissions projections for the plastic lifecycle are inconsistent with meeting the 1.5°C temperature target. If the production, disposal, and incineration of plastic continue on their present growth trajectory, they will undermine global efforts to reduce emissions and keep warming below 1.5°C. By 2030, these emissions could reach 1.34 gigatons per year—equivalent to more than 296 five-hundred-megawatt coal plants.

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Even if growth slows after 2030, plastic production and incineration could emit 2.8 gigatons of CO_2 per year by 2050, releasing as much emissions as 615 five-hundred-megawatt coal plants. Critically, these annual emissions will accumulate in the atmosphere over time. Projected growth in plastic production and incineration will add an estimated 56 million tons of CO_2e through 2050, meaning that plastic alone could consume more than ten percent of the earth's remaining carbon budget.

If lifecycle emissions are considered through the end of the century, the expansion of plastic production and incineration will consume over 125 gigatons of CO_2e—and possibly much more—of the carbon budget. If this scenario becomes a reality, then the plastic lifecycle alone could potentially account for a quarter or more of the global carbon budget for all energy production, industrial activity, transportation, and land use.

Through the Paris Agreement, the nations of the world have committed to keeping global temperature rise "well below 2°C" and further committed to take action with the aim of holding it to 1.5°C. The most recent assessment by the IPCC demonstrates that even 1.5°C of warming poses unacceptable risks, and going beyond that limit is no longer a scientifically or morally defensible goal.

However, current national commitments fall well short of these goals.[344] Therefore, there is no room for increased emissions from plastic production and disposal, as industry plans. On the contrary, governments must seek additional, rapid emissions cuts. As this report demonstrates, the lifecycle of single-use plastic creates both the urgent need and a near-term opportunity for significant emissions reductions and suggests that there are far greater emissions reductions available by targeting plastic and the petrochemical sector generally.[345] Emissions cuts from reducing the production and consumption of plastic are especially attractive because they will help to address other important environmental and social issues, and they will not negatively impact efforts to achieve the Sustainable Development Goals (SDGs).

RECOMMENDATIONS

Heightened awareness and growing public concern about the plastic pollution crisis have inspired numerous plastic pollution mitigation strategies. This report examined several of the most widely promoted strategies according to five criteria: potential to achieve meaningful greenhouse gas emissions reductions; effectiveness as a lifecycle approach to plastic production and pollution; potential benefits or negative impacts on achieving other important social and environmental goals, such as cleaner water, improved air quality, and healthier ecosystems; feasibility and readiness of the solution; and scalability and affordability, which considers whether the strategy can be implemented at a scale sufficient to bring plastic-related emissions in line with climate stabilization targets by 2030 and 2050. The analysis is summarized visually in Table 9, which is adapted from a similar analysis developed by 5Gyres.

High-Priority Strategies

Stop the production and use of single-use, disposable plastic products. Whether evaluated in the context of extraction-related emissions, emissions from plastic manufacturing and incineration, or reducing the impacts of environmental plastic, the most direct and most effective way to address the plastic crisis is to dramatically reduce the production of unnecessary plastic, beginning with national or global bans on nearly all single-use, disposable plastic. Stopping the plastic pollution problem at its source—stopping the production of non-essential plastic—is the surest way to curtail emissions throughout the plastic lifecycle.

A related, complementary, and necessary strategy is to **stop new oil, gas, and petrochemical infrastructure.** The greenhouse gas emissions embedded in existing, proven reserves for oil, gas, and coal already exceed the atmosphere's remaining carbon budget under a 1.5°C scenario. Accordingly, the IPCC's SR 1.5 report emphasizes that a rapid and nearly complete transition away from fossil fuels is vital to keeping aggregate warming below 1.5°C. As documented by CIEL and others, the surplus of cheap natural gas liquids driven by the ongoing fracking boom is fueling a massive expansion of infrastructure for plastic production and manufacture in the United States and beyond. Just as significantly, the construction of these new facilities will create ongoing demand for new

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fossil fuel feedstocks, with implications for human health, the environment, and the climate at every stage of the plastic lifecycle.

Zero-waste systems, including bans on incineration and open burning, reduce plastic-related emissions directly by dramatically reducing the burning of plastic. This includes similar technologies such as gasification, pyrolysis, and plastic-to-fuel. Zero-waste systems also reduce emissions indirectly through improved source separation and collection, as well as upstream approaches like bottled water bans. Moreover, experience in communities around the world demonstrates that zero-waste approaches have significant co-benefits for environmental quality, human health, and livelihoods.

Each of the foregoing strategies complements and benefits from the implementation of **extended producer responsibility for the circular economy**. Modest or even significant increases in recycling will neither solve the plastic crisis nor significantly reduce plastic-related greenhouse gas emissions. When combined with zero-waste communities and bans on new infrastructure, however, extended producer responsibility can ensure that producers of plastic products and fast-moving consumer goods avoid unnecessary plastic production, design products for long and repeated use, and invest in the systemic changes required to make a circular economy succeed.

Finally, reducing the climate impacts of the plastic lifecycle will require that nations **adopt and rigorously enforce ambitious targets for reducing greenhouse gas emissions** from both fossil energy and industrial sources, including the entire plastic lifecycle. Setting these targets will not only address and reduce the greenhouse gas impact of plastic, but also transform the larger fossil economy in which plastic is embedded and help protect communities, human rights, and human lives from the urgent threat of climate change.

Complementary Interventions

Even as the world moves forward on these high-priority strategies to address the plastic and climate crises, this report identifies a number of complementary measures that can reduce plastic-related emissions, reduce the environmental and health impacts of plastic, or both. This includes measures to **reduce or limit construction of new oil, gas, and petrochemical infrastructure** until more comprehensive limits can be put in place.

Identifying and fixing leaking pipes and tanks in the plastic supply chain will not reduce plastic production or the emissions from waste and environmental plastic, but it could dramatically reduce upstream methane emissions that compound plastic's lifecycle greenhouse gas emissions.

Nations must adopt and rigorously enforce ambitious targets to reduce greenhouse gas emissions. Doing so will transform the larger fossil economy in which plastic is embedded and help protect communities, human rights, and human lives from climate change.

Similarly, for existing fossil fuel and plastic infrastructure, **mandating that gas from wells, pipelines, and facilities be captured rather than flared or vented** can reduce an ancillary but important source of emissions, with benefits both for the climate and nearby communities.

Beach cleanups and river controls are labor and resource intensive, but can have important benefits for ecosystems and local communities. These strategies will not meaningfully reduce greenhouse gas emissions, however, and their other benefits may be only temporary unless underlying sources and causes of plastic pollution are addressed.

In appropriate and likely limited circumstances, such as when ghost fishing nets are converted into carpets, **recycling ocean plastic** may make a modest but meaningful contribution to local ecosystems while simultaneously contributing to livelihoods.

Low-Ambition Strategies

Using renewable energy to fuel the plastic supply chain will not solve plastic's climate impacts. As Material Economics noted, a significant portion of greenhouse gas emissions from plastic production comes from the chemical processes involved in plastic manufacturing, emissions that will not be affected by the use of renewable energy. Moreover, producing plastic with renewable energy will do nothing to reduce the downstream emissions from the incineration and disposal of plastic or reduce its impacts on ocean ecosystems and carbon sinks. This assessment applies with still greater force to proposals to **maximize energy efficiency throughout the**

plastic supply chain. While improving energy efficiency in necessary processes is certainly vital, producing an unnecessary and high-emitting product more efficiently does little to safeguard the climate or the planet.

Modern landfilling practices may be a significant environmental improvement over unmanaged waste or unregulated land dumps and thus could be very worthwhile from a community perspective. However, the climate benefits from modern landfilling are marginal at best, and landfilling is, by definition, a disposal solution that will have few benefits for the many upstream impacts of plastic production and use.

Incinerating plastic under the guise of waste-to-energy has the potential to significantly increase greenhouse gas emissions from plastic production while simultaneously increasing toxic exposures for communities both near and far from incinerators.

While the concept of **cleaning plastic from the open ocean** is appealing, such strategies will do nothing to reduce the lifecycle greenhouse gas emissions of plastic; will not address the significant impacts of plastic on land, freshwaters, and coastlines; and will not address the plastic production and waste that give rise to ocean plastic. Such cleanup operations have little potential to capture the vast quantities of microplastic that contaminate the oceans' surface and depths, and biologists have raised concerns about potentially harmful impacts of these efforts on ocean wildlife.

False Solutions

Finally, this report exposes a small number of proffered "solutions" that are unlikely to benefit the climate, communities, or ecosystems. Analysis suggests that, viewed across their respective lifecycles and in the broader context of the climate and plastic crises, these false solutions do not represent useful investments given limited time, resources, and political will.

Biodegradable plastic poses an array of challenges and limitations. Many types of plastic identified as biodegradable can be broken down only with special equipment or under specific conditions that do not exist in most community composting facilities. Even the plastic that does break down may do so to only limited degrees. From a climate perspective, the fact that a plastic is biodegradable says little about the emissions arising from its production and use.

Relatedly, using **bio-feedstocks in petrochemical and plastic manufacturing** may reduce emissions associated with fossil fuel production, while simultaneously generating significant new emissions from land disturbance, chemically and mechanically intensive agriculture, and the harvest, transport, and processing of the feedstocks. Processing bio-feedstocks into plastic will itself produce significant greenhouse emissions. Further, the plastic produced may be chemically identical—or even combined with—fossil-based plastic, thus eliminating the environmental and social benefits of reduced plastic production. **Biodegradable plastic produced from bio-feedstocks** may alleviate some of the latter problems, but would raise the same greenhouse gas concerns as other bio-feedstocks.

Developing and deploying **plastic-eating organisms** will not reduce or address the significant greenhouse gas emissions that occur throughout the plastic lifecycle. Unless released directly into the environment, which would generate significant uncertainties and risks, plastic-eating organisms would be of limited benefit as an end-of-life, and potentially costly, waste management solution for plastic.

Using chemically recycled feedstocks from post-consumer plastic in petrochemical and plastic manufacturing does not hold the promise of true, closed-loop recycling. First, it does not address the high energy demands and emissions associated with plastic production. Second, it relies on post-consumer recovery of plastic that is unlikely to be efficient. Third, it is unsuitable for many common forms of plastic, such as PVC, which must be manually separated out. Fourth, the value of the recovered feedstock is so low compared to virgin feedstock that chemical recycling is not financially viable without heavy government subsidies.

Incinerating plastic under the guise of **waste-to-energy** has the potential to significantly increase greenhouse gas emissions from plastic production while simultaneously increasing toxic exposures for communities both near and far from incinerators. In so doing, waste-to-energy operations transfer the threat of plastic from the oceans to the air, while compounding its climate impacts. This is the very definition of a false solution.

TABLE 9

Recommendations

Strategies	**Greenhouse Gas Emissions** Reduces greenhouse gases or limits emissions growth	**Impact** Lifecycle approach	**Non-Climate Benefits** Will it have +/– impacts on SDGs	**Feasibility/ Deployability** Feasibility/ Is it ready for implementation	**Scalability & Affordability** Can it be implemented cost-effectively at scale
High-Impact Interventions to Reduce Greenhouse Gas Emissions from the Plastic Lifecycle					
Stop the production and use of single-use, disposable plastic products	🟩	🟩	🟩	🟩	🟩
Stop new and expanded petrochemical and plastic production infrastructure	🟩	🟩	🟩	🟩	🟩
Zero-waste communities	🟩	🟩	🟩	🟩	🟩
Extended producer responsibility for circular economy	🟨	🟩	🟩	🟩	🟨
Set and enforce meaningful emissions limits and monitoring requirements for point sources	🟩	🟨	🟩	🟩	🟨
Medium-Impact Interventions that May Benefit Climate or Sustainable Development Goals but Not Both					
Reduce construction of new petrochemical and plastic manufacturing infrastructure	🟨	🟨	🟩	🟩	🟨
Reduce new pipeline and well pad construction	🟨	🟨	🟨	🟩	🟨
Identify and fix leaking pipes and tanks	🟨	🟨	🟨	🟨	🟨
Beach cleanups	🟥	🟥	🟩	🟩	🟨
River controls (catchment areas below artificial barriers)	🟥	🟨	🟩	🟩	🟥
Low-Impact Interventions that Do Little to Safeguard the Climate or the Planet					
Mandate offsetting reforestation projects	🟩	🟨	🟥	🟨	🟩
Use renewable energy sources throughout plastic supply chain	🟩	🟥	🟨	🟨	🟨
Ocean plastic recycling	🟥	🟥	🟩	🟨	🟥
Maximize energy efficiency throughout plastic supply chain	🟥	🟥	🟨	🟩	🟥
Modern landfill	🟥	🟥	🟨	🟩	🟥
Mandate capturing gas vs. loss (flaring/venting)	🟥	🟨	🟨	🟨	🟥
False Solutions					
Biodegradable plastic	🟥	🟥	🟨	🟨	🟥
Use bio-feedstocks in petrochemical and plastic manufacturing	🟨	🟥	🟥	🟨	🟥
Plastic-eating organisms	🟥	🟥	🟨	🟨	🟥
Ocean cleanup	🟥	🟥	🟨	🟥	🟥
Use chemically recycled feedstocks in petrochemical and plastic manufacturing	🟥	🟥	🟥	🟨	🟥
Further integrate petroleum refining, gas processing, petrochemical, and plastic manufacturing	🟥	🟥	🟥	🟨	🟥
Waste-to-energy	🟥	🟥	🟥	🟨	🟥

🟩 High 🟨 Moderate 🟥 Low

CHAPTER NINE

Conclusions

The profound and rising impact of the plastic crisis on ocean ecosystems and marine species has prompted global concern and growing calls for regulation at the local, national, and international levels. Mounting evidence demonstrates that, from wellhead to store shelves to water and food systems, the plastic lifecycle poses risks not only for the environment, but also for human health. Against this backdrop, the present report documents the array of mechanisms through which plastic also compounds the risks of climate change.

In the Paris Climate Agreement, the nations of the world committed to keep climate change to well below 2°C and to pursue efforts to stay within 1.5°C of warming. To date, the earth has warmed just over 1°C due to human activity, yet the devastating impacts of that change are already evident in countries and communities around the world. The overwhelming scientific consensus now demonstrates that warming of even 1.5°C will bring still greater risks and that warming beyond that level would cause irreparable, irreversible harm to ecosystems and still greater losses of human livelihoods, human rights, and human lives. To have any hope of avoiding these outcomes, the world must cut its emissions of greenhouse gases by 45 percent by 2030 and reach zero net emissions by mid-century.

Whether measured by its present scale or projected growth, the existing plastic economy is fundamentally inconsistent with that goal. On its present trajectory, emissions from plastic production and use would exceed the entire remaining carbon budget for all industrial greenhouse gas emissions even under a 2°C scenario. Even modest growth in plastic will make achieving a 1.5°C target virtually impossible. Meeting these targets will require immediate and dramatic reductions in plastic production and use as an essential component of the broader transition from the fossil economy. Accordingly, a fundamental finding of this report is that these climate impacts must play a larger and more explicit role in decisions about plastic policies, plastic production, and plastic-related investments. The ongoing, rapid growth of plastic production can and should appropriately be measured against the earth's rapidly dwindling carbon budget. Every new or proposed facility in the plastic supply chain should be evaluated for its impact on that budget by the corporate decisionmakers that propose it, by the potential investors who must evaluate it, and by the governments that must approve it.

Whether measured by its present scale or projected growth, the existing plastic economy is fundamentally inconsistent with the Paris Agreement.

This report also demonstrates that the true scale of climate risks from plastic, while clearly significant, remains largely unquantified. A recurring and troubling theme of the report is the degree to which entire categories of emissions sources are either inconsistently documented or wholly undocumented in the context of plastic. Plastic is the second-largest and fastest growing source of industrial greenhouse gas emissions, so addressing and closing these gaps should be a high priority.

This report also exposes the profound risks inherent in perpetuating a plastic economy while these information gaps remain unfilled. Nowhere are the risks of this systemic ignorance more evident and more profound than with plastic's impacts on

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the oceanic carbon sink. Though existing evidence is preliminary, and significant knowledge gaps remain, there is mounting evidence that microplastic is being found in the plankton that not only form the base of oceanic food chains but also provide the single most important mechanism for absorbing atmospheric carbon and transporting it to deep-ocean carbon sinks. In oceans around the world—in the North Atlantic, the North Pacific, the Indian Ocean, and the China Sea—zooplankton are being contaminated with microplastic. If, as laboratory experiments suggest, this contamination is having significant effects on the feeding, vitality, and survival rates of these organisms, the implications for the oceanic carbon sink—and for the global climate—are both profound and profoundly troubling. At present, the plastic contamination of oceanic plankton raises more questions than answers. These questions deserve urgent attention.

This report identifies many such questions. It highlights the degree to which the world remains surprisingly ignorant about the lifecycle and the impacts of one of the most ubiquitous products in the global economy and one of the most pervasive contaminants on the planet.

Despite these uncertainties, however, this report demonstrates clearly that the climate impacts of the existing plastic economy are real, significant, and fundamentally incompatible with maintaining a survivable climate.

Endnotes

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237. Global plastic production is estimated to grow at the rate of 3.5- 3.8 percent annually 2015–2030 (ICIS) and 3.5 percent annually 2030–2050 (International Energy Agency World Energy Outlook 2015). A growth rate of 3.65 percent was applied in this analysis as the Ellen MacArthur Foundation report, 'The New Plastics Economy' projected that plastic production will be 1124 million metric tons by 2050. *See* World Economic Forum, *supra* note 12; Ellen MacArthur Foundation, *supra* note 225.

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Plastic & Climate

THE HIDDEN COSTS OF A PLASTIC PLANET

Amidst growing concern about the impacts of plastic on the oceans, ecosystems, and human health, there's another largely hidden dimension of the plastic crisis: plastic's contribution to global greenhouse gas emissions and climate change. This report examines each of these stages of the plastic lifecycle to identify the major sources of greenhouse gas emissions, sources of uncounted emissions, and uncertainties that likely lead to underestimation of plastic's climate impacts. The report compares greenhouse gas emissions estimates against global carbon budgets and emissions commitments, and it considers how current trends and projections will impact our ability to reach agreed emissions targets. It also compiles data, such as downstream emissions and future growth rates, that have not previously been accounted for in widely used climate models. This accounting paints a grim picture: plastic proliferation threatens our planet and the climate at a global scale.

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