U.S. House Committee on Energy and Commerce
Subcommittee on Environment, Manufacturing, and Critical Materials
"America Leads the Way: Our History as the Global Leader at Reducing Emissions"
[November 29, 2023]

1. A report prepared by Energy Policy Center and Cleveland State University entitled "Economic Impact of the Muskingum Watershed Conservancy District on the Regional Economy, 2014-2022" November 13, 2023, submitted by Rep. Balderson.
2. A letter to Chair Johnson and Ranking Member Tonko from the Portland Cement Association, November 29, 2023, submitted by the Majority.
3. Report by Business Roundtable entitled "Strengthening Global Clean Energy Supply Chains" submitted by the Majority.
4. An article from the International Energy Agency entitled "Oil and Gas Industry Faces Moment of Truth – and Opportunity to Adapt – as Clean Energy Transitions Advance," November 23, 2023, submitted by the Minority.
5. An article from the New York Times entitled "U.S. and China Agree to Displace Fossil Fuels by Ramping Up Renewables," November 14, 2023, submitted by the Minority.
6. A report from the U.S. Global Change Research Program entitled "Fifth National Climate Assessment" submitted by the Minority.
7. A press release from the World Resources Institute, November 14, 2023, submitted by the Minority.
8. A report by the Intergovernmental Panel on Climate Change entitled "Climate Change 2023 Synthesis Report" submitted by the Minority.
9. A paper from Robert W. Howarth entitled "The Greenhouse Gas Footprint of Liquified Natural Gas (LNG) Exported from the United States," October 24, 2023, submitted by Rep. Barragan.

CSU | Levin College of Public Affairs and Education

Economic Impact of the Muskingum Watershed Conservancy District on the Regional Economy, 2014 - 2022

November 13, 2023

PREPARED BY: ENERGY POLICY CENTER
CLEVELAND STATE UNIVERSITY

PREPARED FOR: MUSKINGUM WATERSHED CONSERVANCY DISTRICT

Acknowledgements

Mark Henning, EPC Research Supervisor: designed and led the data collection, aggregation and conditioning, and prepared the data for use in the input-output models.

Contact Information: m.d.henning@csuohio.edu

Dr. Randall Jackson, Emeritus Professor of Economics, Geography, and Public Policy and former Director of Regional Research Institute at West Virginia University (specializing in economics, input-output analysis, regional development, impacts assessment, and forecasting): Dr. Jackson designed the data conditioning process, and performed the analysis using IO-Snap, a prominent software application that supports all aspects of fundamental input-output analyses.

Dr. William Bowen, Emeritus Professor of Public Administration and Urban Studies at Cleveland State University (specializing in regional analysis, economic development, environmental issues, and energy policy): Dr. Bowen led the review and interpretation of the output data, and the preparation of this report, with the support of the team.

Photos curtesy of Muskingum Watershed Conservation District

Table of Contents

List of Tables

Executive Summary

The Muskingum Watershed Conservancy District (MWCD), serving all or parts of 18 counties in Eastern Ohio, has made a significant economic contribution to the regional economy since initiation of its Master Plan for park capital improvements in 2014, enabled by growing revenues derived from Utica and Point Pleasant (together, "Utica") oil and gas leases.[1] This study assesses the economic impact of both construction projects and operations by MWCD in those 18 counties from 2014 through 2022.

MWCD 18-County Regional Economic Impact

The capital expenditures analyzed in this study occurred between 2014 and 2022 in conjunction with MWCD's multiyear capital improvement plan. Over these nine years, a total of 2,287 jobs were created to implement this Master Plan for improving the conservancy district's facilities, paying out $135.6 million in wages and benefits (see Table 1). This labor income was the combined amount earned directly by construction workers, indirectly by employees in supply chain industries that supported construction projects, or induced by workers in direct and indirect industries who spent their earnings on local goods and services. Total value added—the impact of MWCD's capital expenditures after netting out the costs of intermediate inputs—was $221.9 million, and gross output (the sales or revenue from production for industries) was $486.8 million.

Operations and maintenance (O&M) performed by MWCD supported 319 jobs on average annually from 2014-2022, with $18.1 million in wages and benefits per year. Total value added stemming from O&M was $26.5 million per year on average, with gross output exceeding a little over $50 million annually.

Altogether, the total direct, indirect and induced impacts on the region from MWCD's $310.9 million in spending on capital improvements and annual O&M during the nine-year study period was in excess of $938 million (see Gross Output column in Table 1). Even after subtracting out the costs of intermediate inputs in order to avoid double counting whereby more than one link in a supply chain can lay claim to the same gross output, MWCD's total expenditures over this time represented a benefit of more than $460 million to the region (see Value Added column in Table 1).

Table 1: Total Economic Impact of MWCD Capital & Operating Expenditures in the 18-County Region for 2014 - 2022

Period	Expenditures	Employment[2]	Labor Income	Gross Output[3]	Value Added[4]
Annual average	Capital	254	$15.1 M	$54.1 M	$24.7 M
	O&M	319	$18.1 M	$50.2 M	$26.5 M
	Combined Total	**573**	**$33.2 M**	**$104.3 M**	**$51.2 M**
Total for 2014 - 2022	Capital	2,287	$135.6 M	$486.8 M	$221.9 M
	O&M	319	$162.8 M	$451.5 M	$238.9 M
	Combined Total	**2,606**	**$298.4 M**	**$938.3 M**	**$460.8 M**

All monetary figures are in $2021 dollars.

In 2022, MWCD leased more than 7,300 acres in Harrison County, OH that will generate bonus payments in excess of $40 million.[5] MWCD anticipates millions more will be paid in royalties from this lease. Spending resulting from this lease agreement is not reflected in this study, although these revenues will catalyze further economic impact through capital improvements and ongoing operations in 2023 and beyond.

1. Introduction

The Muskingum Watershed Conservancy District (MWCD) is a government entity in Ohio, USA, responsible for managing water resources within the Muskingum River watershed. MWCD provides flood control, conservation and recreation throughout the 8,000 square mile watershed district, which covers 20% of the State of Ohio and includes all or part of 18 counties. It was established in the 1930s to address flooding issues and promote water conservation in the region. The MWCD operates a system of dams and reservoirs, including Charles Mill Lake and Seneca Lake, to regulate water flow, control floods, and provide recreational opportunities. The district plays a crucial role in balancing the needs of various stakeholders, including agriculture, industry, and environmental conservation.

From its inception, MWCD inherited oil and gas wells and existing leases with lands it acquired. MWCD added to this oil and gas program, by which acreage primarily on MWCD lands is leased to private operators in return for oil & gas royalties that support the district's operational expenses and enable it to make various recreational and other contributions to the region. Leases for traditional vertical oil and gas wells on MWCD lands that it had negotiated over the past decades have included landowner and environmental protections that were cutting edge at the time.

Prior to 2010, the annual amount of oil & gas production in Ohio was modest, at best. However, the success of operating companies using horizontal drilling and hydraulic fracturing techniques to maximize the recovery of oil and gas in a well in the Marcellus Shale in Pennsylvania, led operating companies in 2011 to come to Ohio to drill—and to successfully produce—the first horizontal wells in the Utica formation.

In 2010-2011, MWCD was presented with the opportunity to recover its minerals from these new horizontal wells. This decision was going to be important to not only the organization, but also the surrounding private lands, and oil and gas production in Ohio. MWCD would then negotiate new custom provisions and safeguards into its standard oil and gas lease and further those protections to these new horizontal wells.

Thereafter, drilling and production activities increased quickly, going from 9 wells producing the equivalent of 2.8 billion cubic feet of natural gas in 2011, to over 810 wells producing the equivalent of 511.6 billion cubic feet in 2014.[6] MWCD likewise saw a significant increase in oil & gas related revenues during this period, going from about $322,000 in average annual lease bonus payments and royalties for 2008-2010, to $28.1 million in average annual payments for 2011-2013, to $41.0 million in average annual payments for 2014-2016.[7]

In 2022, MWCD and a large operator agreed to a lease that covers more than 7,300 acres in Harrison County, OH. Similar to previous MWCD agreements, the lease contains mutually-agreed-upon criteria to mitigate risks to human health & safety, the environment, the watershed, and regional stakeholders.

Since 2014, when shale development in Ohio first began to annually generate billions of dollars' worth of drilling investment and production revenues, MWCD has received around $270 million in bonus payments and royalties from its oil and gas leases.[8] These revenues have enabled the conservancy district to develop or improve a range of facilities in the area, including construction of the $5 million water treatment plant at Atwood Lake, nearly $9 million in renovations at the Charles Milles main campground (including upgrades to utilities and new restroom & shower buildings), $10 million in long-term maintenance dredging at Tappan Lake, and about $13 million for redevelopment of Seneca Lake's Marina Point campground, including utility upgrades, new restroom/shower houses and shelters, and construction of more than 100 new RV sites.

Development of the Utica Shale has generated revenue for MWCD that has enabled it to bring economic benefits to the conservancy district's 18-county service area, including job creation, increased tax revenues, and growth in related industries such as transportation and infrastructure. This research does not consider the downstream effects of lower priced natural gas on the regional economy resulting from development on its leases. Nor does it consider environmental impacts from this development. However, the conservancy district has embedded environmental stewardship into its mission and practice, committing millions of dollars toward strengthening conservation and sustainability.[9] In accordance with its mission of responsible stewardship, MWCD has instituted operational safeguards, land management practices, and environmental protections into its leases that exceed the standard requirements found in most lease agreements (or required by Ohio environmental regulations).[10]

Increases in oil and gas revenues associated with Utica Shale development have enabled MWCD to greatly expand its scope to the point at which it now provides some of the best recreational opportunities in Ohio. It has for example made capital improvements including upgrades or construction of cabins, campgrounds, docks, playgrounds, picnic shelters, shower houses, trails, and wastewater utilities infrastructure.

MWCD has also made investments in conservation including (a) Nutrient Management Programs, (b) Cover Crop Programs, (c) Water Quality Testing and Research, (d) purchase of approximately 6000 acres in Willis Creek, (e) Acid Mine Drainage Mitigation, (f) Abandon Well Program, (g) Sustainability Programs, and (h) the Partners in Watershed Management Program. The Partners in Watershed Management Program has, for example, helped distribute more than $10 million dollars in enhanced flood mitigation grants throughout MWCD's entire service area since 2009 to address storm water management issues and to provide assistance to local communities for conservation and flood control projects that are consistent with the conservancy district's mission.[11]

In 2023, the MWCD contacted the Energy Policy Center (EPC) at Cleveland State University, declaring its interest in coming to better know and understand what sort of economic impact all of these investments and improvements have had on the regional economy. An EPC team agreed to estimate these impacts using input-output (IO) analysis.

Input-output analysis is a macroeconomic, data-driven analytical technique based on data that measure the interdependent flow of resources between different economic sectors or industries. It is widely employed to estimate the impacts of economic shocks, such as MWCD's expenditures in the region, and to analyze the ripple effects throughout the economy. It is specifically based upon data known as "input-output tables" depicting rows and columns of flows of dollars that quantify the supply chains for all of the sectors of an economy. All sales and purchase transactions are expressed in financial rather than physical units.

Three types of impacts are modeled in input-output analysis, as explained in more detail below: direct impacts, indirect impacts, and induced impacts. IO analysis determines the overall economic impacts on a region's economy when certain input levels—such as amounts of MWCD investments and improvements—are changed.

2. Literature Review & Terminology

Input-output analysis is rooted in economics and based on the simple but fundamental notion that the production of economic output requires inputs, and that these can be monetized. The inputs may take the form of raw materials or semi-manufactured goods supplied by firms in the various industrial sectors, or inputs of services supplied by households or government. Households provide labor inputs, while the government supplies a range of services such as farmland preservation, law enforcement, programs that promote healthy small businesses, and the road system. Having purchased inputs from producing sectors, or primary inputs from households, each firm or other entity in a given supply chain then produces a range of outputs, some of which become inputs into other chains. By accounting for these flows of goods, services and resources through multiple rounds of exchange and production throughout a region's economy, the analytical framework allows for a comprehensive understanding of how various sectors within a region interact with and depend on each other.

The input-output analytic approach has proven itself over many years to be a valuable tool in assessing the regional economic impacts of various economic activities and shocks on regional economic systems. It's use in assessing regional economic impacts has evolved over time, gaining prominence for its ability to provide a holistic view of the interconnectedness and impacts of economic activities (Bjerkholt and Kurz, 2006; Hewings, 2020; Miernyk, 2020; Miller and Blair, 2009; Rose and Miernyk, 1989; West, 2020). In addition to the analysis of the effects of various economic shocks, input-output analysis has been used extensively in regional economic modeling, environmental impact assessment, and policy analysis. It is widely used to help to analytically assess the potential consequences of economic activities and policies, such as tax changes, infrastructure investments, or shifts in consumer preferences. See the Technical Appendix for a more detailed introduction.

Input-output analysis has also been applied to assess the economic impact of various water-related events and activities. These include regional water planning (Daniels, Lenzen, and Kenway, 2011), agricultural water management (Sun et al., 2021), and the impact of water supply reductions in the Great Lakes (Garcia-Hernandez and Brouwer, 2021). The IO method can help in understanding how changes in—or expenditures by—one such water-related activity can reverberate throughout the regional economy. For example, when MWCD invests in infrastructure improvements or implements new technologies, this leads to direct and indirect effects on employment, income, and overall economic activity throughout the region.

One of the key insights derived from the input-output model is the concept of multiplier effects. The basic idea is that an initial infusion of dollars into a regional economic system changes hands again and again with additional transactions within the region, but the amount diminishes with each successive transaction. The amount diminishes for a couple of reasons. As dollars repeatedly change hands, leakages from the region's economy occur in the form of taxes, imports and savings. Spending also diminishes through successive rounds because part of the payment to a producer for a product goes to labor (and other value added), which means that the total value of demand for intermediate inputs will be less and less at each successive upstream link in the supply chain. Accordingly, when there is an increase in demand or investment in one sector of the economy, this effectively generates a series of ripple effects throughout the entire regional economic system. These effects can be summarized using multipliers, which show how changes or shocks in one industrial sector's output or expenditures affects other sectors. A high multiplier means that once the ripple effects have been considered, the change in that sector has a big impact upon overall output, employment, income or value added, depending on the particular multiplier in question. The key is to understand that input-output multipliers are estimated in terms of direct, indirect, and income-induced effects.

Direct effects reflect the initial changes in economic activities, such as an increase in investment by MWCD in monitoring the containment of shale drilling effluent. They are like the first domino in a chain. For example, if MWCD were to sign a $500,000 contract with Firm A to monitor the integrity of a set of wastewater tank containment berms, this is a direct expenditure or direct effect. (These containment berms—often made of PVC-coated fabric—are flat protective barriers with walls along the edges that are placed under equipment such as storage tanks to contain leaks and spills.)

The **indirect effects** reflect the fact that Firm A will spend the aforementioned $500,000 for purposes of fulfilling the terms of the contract. They might hire trained personnel to check for proper installation of spill containment berms, ensure that they are correctly positioned around the wastewater tank, perform regular visual inspections and routinely look for signs of wear, damage, or any visible issues with the berms. They may purchase infrared and conductivity sensors for real-time leak detection, remote monitoring systems to sense liquid levels, temperature and pressure, or geospatial monitors for the structure or displacement of the berms through satellite imagery. And they will probably hire inspectors to ensure adherence to industry regulations and standards for environmental compliance. All of this spending by Firm A necessary to accomplish the requirements of the primary contract with MWCD are the secondary or indirect effects of MWCD's direct investment.

When indirect effects of MWCD's investments are all monetized and aggregated across all of the sectors of the economy, and when these are compared to the direct effects, this produces a multiplier. The multipliers show how many times the direct $500,000 output initially invested by MWCD circulates in the regional economy.

Multipliers are calculated for industrial output, employment, household compensation (income), and other value added.[12] Industrial output multipliers reveal the number of times the dollar value of direct industrial output increases as a result of indirect and induced effects within the study area, before it leaks from the regional economy.[13] Employment multipliers show the number of times the indirect and induced effects of spending within the region increase the number of jobs directly supported by the initial change in economic activity. Household income multipliers show the number of times the increase in household income directly attributable to the initial change in economic activity gets multiplied by the corresponding indirect and induced spending. Value added multipliers reveal the ratio of total value added after the indirect and induced spending has occurred to the total value added that occurs as a direct result of the initial change in activity alone.

The multipliers reported herein take account not only of indirect but also of **induced effects** or changes in regional output, employment, income and value added resulting from increased consumer spending.[14] For example, to extend the same example used previously, the spill containment berm inspectors hired by Firm A might spend the part of the $500,000 they earn in salary on some new clothes for their children, or on automobile maintenance, or haircuts at the local barbershop. These dollars that run through households comprise the induced effects of MWCD's investments, and they are found and monetized through increased household spending. Income induced demand then triggers additional indirect and induced income impacts as it once again stimulates demand in upstream supply chain industries.

The regional focus of input-output analysis can be particularly advantageous when measuring the effects of economic shocks. It can for instance allow the assessment to be tailored to the specific district's geographic areas, such as the specific MWCD study area analyzed in this report, recognizing the unique economic structures and dependencies within the region. Moreover, input-output analysis facilitates the identification of the impacts of the shock upon key sectors that play pivotal roles in the regional economy.

Input-output analysis assumes that the least common denominator of analysis occurs at the level of a commodity or industry. The distinction between commodities and industries is that commodities are made by industries. Industries are composed of groups of firms that produce commodities. They are usually organized and codified using the North American Industrial Classification System (NAICS), which aggregates economic activity by highly similar goods or services and businesses. Commodity data, which can also be assigned to NAICS codes, show the supply of specific commodities by each industry in the economy, and the commodities each industry uses to produce its output.

By understanding the inter-industry relationships within a given study area, stakeholders can pinpoint sectors with high multiplier effects, indicating a strong influence on overall economic activity. This information can be invaluable for strategic planning and resource allocation, guiding efforts to enhance the resilience and sustainability of regional economies.

Uses of input-output analysis to assess regional economic impacts, such as the one in this report by the EPC team, have become a cornerstone in economic research and policymaking. The ability of input-output analysis to provide a nuanced understanding of inter-industry relationships, direct, indirect and induced effects, and sectoral contributions makes it an invaluable tool for crafting targeted strategies to understand and foster regional development. As technology and methodologies continue to advance, input-output analysis is likely to remain a fundamental component of regional economic analysis, guiding efforts to build resilient and sustainable economies.




3. Research Methods

3.1 Data

The data for regional input-output analysis come from regional input-output accounts. Subsets of these accounts, namely the Use and Make tables, provide the parameters that populate the analytical tables on which IO analysis is founded. In these tables, the outputs of one sector become the inputs to another. Purchasing sectors are listed across the top of the table, and producing or selling sectors are listed down the left-hand side of the table. The values in each cell are sales from the producing or selling sector named at the left to the sector named at the top. In effect, these tables capture the value of the transactions along the supply chain for all commodity and industrial sectors of the economy.

The input output tables used in this research are derived from data published by the U.S. Department of the Census and U.S. Bureau of Economic Analysis (BEA) at the U.S. Department of Commerce. Published data used include the annual input-output accounts, employment, gross industry product and its components, government expenditures, and personal income by state and industry, by state and industry, along with personal consumption expenditures by commodity. These comprehensive accounts provide the basis for a detailed set of commodity and industry transactions that express in financial units the goods and services produced by each industry and the use of these goods and services by industries and final users.[15]

The BEA tables were customized for the MWCD study region (i.e., "regionalized") using established methods described in Jackson and Járosi (2020a). Data for 18 Ohio counties were included in the MWCD study region. These included Ashland, Belmont, Carroll, Coshocton, Guernsey, Holmes, Harrison, Knox, Licking, Morgan, Muskingum, Noble, Richland, Stark, Summit, Tuscarawas, Wayne, and Washington counties.

Standard analytical procedures were used to factor two groups of MWCD expenditures into the input output tables for the MWCD study area and to estimate their direct, indirect, and induced impacts on production within other industries. These groups were expenditures for (1) development or improvement of facilities, and (2) annual spending on operations and maintenance.

3.1.1 Data for Spending on Development or Improvement of Facilities

MWCD began receiving revenue from shale-related oil and gas development in 2014, and this was also the year in which the district's capital improvement plan (i.e., its Master Plan) began to be implemented. Therefore, data on MWCD expenditures were gathered on a project-by-project basis for 2014 - 2022.

MWCD provided access to its cloud-based accounting software to the EPC team. This platform includes detailed historical data for expenses, expenditures, vendor information, and project information. The MWCD also provided to the EPC team annual Construction in Progress (CIP) Excel workbooks going back to 2014. The CIP workbooks are the district's means of tracking the completion of projects in accordance with the Master Plan. The projects across the 2014 - 2022 CIPs encompass the universe of spending items for which data were gathered.

Within a given year's CIP workbook, there are separate worksheets for each project under development (e.g., a new waste water treatment plant, or a new campground area). Each worksheet lists every vendor involved in that project, as well as the amount MWCD paid to that vendor on that project. Vendors were involved in either construction or non-construction activities, with the latter including such things as architectural and civil engineering firms that designed and planned projects, or newspapers in which public notices were made.

For vendors involved in construction, the project worksheets within a CIP workbook included a pay application reference number linked to a vendor that worked on that project. A pay application is a detailed construction invoice a contractor submits to provide information about the progress of a contract, and also to request payment for work completed. Portable Document File (PDF) copies of these pay applications were available for download to EPC through MWCD's online accounting platform. These PDFs include itemized details of spending for construction activities, such as how much was spent on cement, how much on PVC pipes, or how much on landscaping. This allowed for construction spending to be broken down by subcategory and grouped by U.S. Bureau of Economic Analysis (BEA) industry code. (There are 71 BEA industries.) BEA industry codes generally follow NAICS codes and are tied to the BEA's input-output accounts that are the building blocks for economic impact analysis. Altogether, the EPC team gathered 112 total pay applications, each with an average of 74 spending line items that were assigned a BEA industry code based on the material or activity described therein.

For non-construction vendors, in lieu of a pay application reference number, the project worksheets within a CIP workbook included a brief description of the work performed by the vendor for that project. Such descriptions included the following: design services; geotechnical services; asbestos surveys; electrical engineering services; and well testing. Spending for non-construction activities was aggregated by BEA industry code based on these descriptions. If the appropriate BEA industry code did not seem obvious based on the description or vendor name, the EPC team consulted the business information databases Data Axle and Mergent Intellect, both of which include fields for NAICS codes that have been associated with specific companies. These NAICS codes were translated to BEA's industry classification system using a BEA crosswalk.[16]

The detail available in the pay applications and online accounting software allowed the EPC team to determine the year in which expenditures occurred for all improvement projects and spending items. All spending amounts were converted from nominal dollars to $2021 dollars using the GDP deflator for the United States.[17] These constant-dollar amounts for all spending on improvements from 2014 through 2022 were then summed by BEA industry code and across all years.

These totals represent the economic shock by industry provided by MWCD's development or improvement expenditures. They were entered as input values into the IO-Snap input-output (IO) analysis software. Altogether there were about 200 separate improvement projects over this timeframe.

3.1.2 Data for Average Annual Spending on Operations and Maintenance

Operations and maintenance data were gathered for the period from 2014 through 2022 to match the timeframe for which improvement expenditure data were gathered. MWCD's online accounting platform allows for running expense reports by year that can include transaction-level detail. For each transaction, the vendor can be identified. There are also fields in the expense reports that include the general type of expense account against which the transaction was charged (e.g., Materials & Supplies, Utilities, Operating Equipment) and that can also include a more detailed description of the transaction's purpose.

Altogether, data for roughly 87,000 such transactions were gathered for spending drawn from MWCD's general maintenance fund. Spending for operations and maintenance (O&M) was aggregated by BEA industry code for these transactions using the fields in the expense reports for vendor name, general account type, and detailed description (if available). If the appropriate BEA industry code did not seem obvious upon reviewing these fields, the EPC team consulted the Data Axle and Mergent Intellect business information databases. The EPC team would also visit company websites when necessary to determine a given vendor's line of business.

All spending amounts were converted from nominal dollars to $2021 dollars using the GDP deflator for the United States. These constant-dollar amounts for all spending on O&M for 2014 through 2022 were then summed by year and by BEA industry. The mean of spending on O&M across all years was taken for each BEA industry, representing the economic shock provided by MWCD for spending on operations and maintenance.

These amounts for average annual spending were then entered as input values into the IO-Snap input-output (IO) analysis software.

3.2 Analysis

Input-output analysis requires the data about industries and industrial sectors to be conceptually divided into two major categories. The first of these is composed of economic activities that are considered to be determined outside of or independently of the basic, given structure of the region's economy. These external activities are the economic shock or driving force of the change that makes the impacts estimated by the analysis. In this study, the MWCD expenditures were thus considered to be the external, independent, driving factors of change in the MWCD study area's economy. The other category is composed of activities that are considered to be fixed and determined from within the structure of the production functions and supply chains for all sectors of the regional economy. These comprise the processing sector. The monetized relationships between the activities in the processing sector reveal the industrial structure of the regional economy. In this study, the customized input-output tables for the MWCD study area were thus considered to show the industrial structure of the processing sector.

The analytical procedure used in input-output analysis effectively transmits changes in the external, driving force behind the change through the fixed, determined industrial structure of the region in successive and diminishing rounds of spending. These successive rounds are the ripple effects that are captured in the multipliers. In the MWCD analysis, MWCD's expenditures and investments were assumed to be the driving force of change, and the production functions and supply chains found within the study area's industries, as well as within its households and governments, were considered to be the fixed structure of the economy within the study region.

To account for secondary production demand,[18] expenditures by commodity were transformed to expenditure demand by industry using established methods.[19] This transformation is needed for conformability with the inter-industry input-output modeling formulation used to report the impacts.

While both commodities and industries can be assigned to BEA-code categories, data from Ohio are readily available to relate employment and compensation to industry output, but not to commodity output. Therefore, while the direct effects of MWCD expenditures are reported both in terms of commodity and industry, all of the other results are reported exclusively in terms of BEA industrial sectors. The transformation from commodity to industry also helps to account for the region's (in)ability to completely satisfy local demands. See Jackson, R. and P. Járosi (2020a) for mathematical foundations.

The following six summary tables, broken down by industrial sector in the next section, enumerate the relevant results of the input-output analysis of MWCD investments and expenditures.

4. Findings

The following describes the results of the two separate analyses, one for the MWCD expenditures associated with developing and/or improving new facilities, and a second for the expenditures associated with operations and maintenance.

4.1 Impacts of MWCD Expenditures for Development or Improvement of Facilities

The total dollar output impact of MWCD's $182,145,314 direct expenditure to industry for improvement of facilities over the 2014-2022 period was $486,783,349, meaning that each dollar expended was turned over 2.67 times before leaving the 18-county regional economy that comprises the conservancy district's service area.[20] These dollars directly supported 1092 jobs, $74,124,301 of income, and $106,987,419 in value added within the study region.[21] (The average compensation for these direct jobs was $67,887.)[22] As these dollars circulated throughout the regional economy, the indirect and induced effects increased these numbers to 2287 jobs (employment multiplier = 2.09), $135,555,232 in income (income multiplier = 1.83), and $221,940,869 in value added over the period (value added multiplier = 2.07).

Of the MWCD direct improvement expenditures for commodities over the study period, 86% went to three sectors: manufacturing products ($87,820,647), professional and business services ($33,073,287), and payments to households ($35,566,044). In turn, once these MWCD expenditures were turned over and over in the regional economy, as per the multiplier effects, the total impact on these three sectors alone was $123,793,123 and 330 additional jobs in manufactured products, $39,021,371 and 295 additional jobs in professional and business services, and $135,515,695 and 524 additional jobs through payments to households, respectively.

New full-hookup RV campground at Atwood.

Table 2 is a log of how the total MWCD expenditures for development or improvement of facilities was distributed across commodities and industries. These values were obtained, as described above, by the research team's assignment of a BEA industry code based upon the material or activity described in the MWCD records. They represent the magnitude of the initial economic shock to the regional economy provided by MWCD expenditures for improvements, distributed by commodity and industry.

Table 2. Direct Commodity and Industry Output Impacts of MWCD Improvement Expenditures by Sector (2014-2022)

Sector	Direct Output Impacts by Commodity ($)	Direct Output Impacts by Industry ($)
Agriculture, Forestry, Fisheries	3,313,318	$3,306,677
Mining	8,066,386	$8,044,863
Utilities	1,199,572	$788,703
Construction*	26,056	$35,599
Manufacturing	87,820,647	$92,033,406
Wholesale	4,595,262	$4,541,337
Retail	49,464	$375,178
Transportation	797,555	$834,655
Information	818,630	$3,506,005
Finance, Insurance and Real Estate	4,919,322	$4,922,118
Professional and Business Services	33,073,287	$23,625,611
Education, Health Care, Social Assistance	---	$639,211
Arts, Entertainment, Accommodation, And Food Service	31,866	$108,984
Other Services excluding Government	802,704	$672,280
Government	1,065,241	$3,144,682
Households	35,566,004	$35,566,004
Total	**182,145,314**	**182,145,314**

Notes. The conversion from commodity space to industry space makes an adjustment for the region's ability to supply its own demands. Direct output by industry is typically less than direct output by commodity. The difference is primarily attributable to imports into the study area. This means that industry direct output (demand) will all be satisfied by intraregional production, but commodity direct output (demand) will be partly satisfied by imports.

*The relatively small amount for Construction expenditures is a result of breaking down spending on activities and materials required for capital improvements and allocating it—prior to performing the economic impact analysis—to the sectors that provided these inputs (e.g., Manufacturing, Households, etc.).

Table 3 shows the total economic, employment and income impacts of MWCD improvement expenditures by industrial sector for the period 2014-2022.

Table 3. Total Economic, Employment and Income Impacts of MWCD Improvement Expenditures by Sector (2014 – 2022)

Sector	Total Impacts ($)	Total Employment Impacts (Added Jobs)	Total Income Impacts ($)
Agriculture, Forestry and Fisheries	4,292,680	35	307,581
Mining	8,326,713	17	950,971
Utilities	5,880,540	7	1,038,467
Construction	1,965,667	13	664,186
Manufacturing	123,793,123	330	26,066,066
Wholesale	19,852,277	68	5,946,636
Retail	18,183,554	165	5,715,301
Transportation	11,397,612	73	3,862,792
Information	8,254,492	20	1,695,542
Finance, Insurance and Real Estate	49,200,002	121	5,304,326
Professional and Business Services	39,021,371	295	17,838,593
Education, Health Care and Social Assistance	31,798,368	286	17,167,978
Arts, Entertainment, Accommodation and Food Services	10,134,098	150	3,588,003
Other Services excluding Government	7,139,319	107	3,397,653
Government	12,027,837	77	6,445,134
Households	135,515,695	524	**
Total	**486,783,349**	**2,287**	**99,989,228**

Notes. ** Total household impact is the same as total income impact for households.

Table 4 gives input-output estimates of the direct and total value added to the regional economy. As described earlier, these estimates represent the sum of household compensation, payments to government, and gross operating surplus (i.e., profits) in the respective industries. Value added for the Government "industry" seen in Table 3 is defined as it is in value added for the other industries, although the bulk of the dollar value for Government value added is compensation, since intra-sectoral Government payments to Government, and gross operating surplus, are minimal or zero.

Table 4. Value Added Impacts of MWCD Improvement Expenditures by Sector (2014 – 2022)

Sector	Direct Value Added ($)	Total Value Added ($)
Agriculture, Forestry, Fisheries	1,107,499	1,547,873
Mining	4,496,575	4,049,557
Utilities	507,161	3,781,370
Construction	17,881	987,315
Manufacturing	39,264,946	50,614,854
Wholesale	2,717,843	11,880,945
Retail	219,133	10,718,795
Transportation	367,545	5,615,864
Information	2,046,253	4,697,388
Finance, Insurance and Real Estate	3,125,277	31,717,629
Professional and Business Services	14,665,753	23,917,168
Education, Health Care, Social Assistance	421,267	19,369,808
Arts, Entertainment, Accommodation, And Food Service	72,217	5,576,505
Other Services excluding Government	403,694	4,287,056
Government	1,988,368	7,612,739
Households	35,566,004	35,566,004
Total	**106,987,419**	**221,940,869**

The total value added impact of MWCD's $182,145,314 direct expenditure for improvement of facilities over the 2014-2022 period was $221,940,869 (value added multiplier = 2.07). This total value added impact of $221.9 million represents how much total MWCD expenditures for improvements benefitted the region even after netting out the costs of intermediate inputs, both from within and from outside the study area.

The MWCD total direct expenditure to the household sector (an output) is a part of the initial, external shock whose impacts are estimated by the analysis, not a part of the structure of the production functions and supply chains found within the regional economy. Thus, to avoid double-counting, the dollars used in this expenditure are not included in the calculations used to estimate the multipliers. Therefore, to accurately estimate the total income impacts of the expenditure, the value of total direct expenditures to the household sector for the MWCD improvements must be added to the sum of total income impacts based upon the multipliers. Accordingly, the total income impacts in the study area of the MWCD expenditures for improvements is $99,989,228 + $35,566,004 = $135,555,232.

4.2 Impacts of MWCD Average Annual Expenditures for Operations and Maintenance

The total dollar impact of MWCD's $14,308,281 average annual direct expenditure to industry for operations and maintenance over the 2014-2022 period was $50,166,461, meaning that each dollar expended was turned over 3.51 times before leaving the regional economy. Each year, these dollars directly supported 164 jobs, $10,213,475 of income, and $11,824,639 in value added on average within the study region. (The average compensation for these direct jobs was $62,289.) As these dollars circulated throughout the regional economy, the indirect and induced effects increased these number to 319 jobs (employment multiplier = 1.94), $18,088,493 in income (income multiplier = 1.77) and $26,543,873 in value added (value added multiplier = 2.24) annually over the time period.

Of the MWCD for operations and maintenance expenditures for commodities over the study period, a total of 79% went to utilities ($1,377,171) wholesale ($1,167,821) professional and business services ($1,702,620), and payments to households ($8,029,368). In turn, once these MWCD expenditures were turned over and over in the regional economy, as per the multiplier effects, the total impact on these four sectors alone was $25,497,635 and a total of 167 additional jobs in the region.

Table 5 is a log of how the total MWCD expenditures for operations and maintenance was distributed across commodities and industries. These values were obtained, as described above, by the research team's assignment of a BEA industry code based upon the material or activity described in the MWCD records. These represent the magnitude of the initial economic shock to the regional economy provided by MWCD average annual expenditures for operations and maintenance, distributed by commodity and industry.

Table 5. Average Annual Direct Commodity and Industry Output Impacts of MWCD Operations and Maintenance Expenditures by Sector (2014-2022)

Sector	Direct Output Impacts by Commodity ($)	Direct Output Impacts by Industry ($)
Agriculture, Forestry, Fisheries	4,545	2,961
Mining	63,331	30,254
Utilities	1,377,171	876,007
Construction	72	344
Manufacturing	308,483	294,826
Wholesale	1,167,821	1,055,518
Retail	624,496	523,833
Transportation	9,177	15,311
Information	495,777	309,215
Finance, Insurance and Real Estate	544,791	487,806
Professional and Business Services	1,702,620	1,235,013
Education, Health Care, Social Assistance	135,692	93,451
Arts, Entertainment, Accommodation, And Food Service	94,067	74,750
Other Services excluding Government	161,458	130,030
Government	734,851	1,149,595
Households	8,029,368	8,029,368
Total	**15,453,719**	**14,308,281**

Table 6 shows the total economic, employment and income impacts of MWCD expenditures per year on average for operations and maintenance by industrial sector for the period 2014-2022.

Table 6. Average Annual Total Economic, Employment and Income Impacts of MWCD Operations and Maintenance Expenditures by Sector (2014 – 2022)

Sector	Total Impacts ($)	Total Employment Impacts (Added Jobs)	Total Income Impacts ($) *
Agriculture, Forestry and Fisheries	237,810	2	16,705
Mining	170,896	0	13,269
Utilities	1,460,282	2	257,877
Construction	234,566	2	79,258
Manufacturing	4,092,501	10	790,726
Wholesale	2,494,641	9	747,256
Retail	2,864,689	26	903,079
Transportation	892,085	6	308,388
Information	1,033,750	3	213,588
Finance, Insurance and Real Estate	6,201,165	15	670,498
Professional and Business Services	3,454,219	28	1,553,443
Education, Health Care and Social Assistance	4,274,236	39	2,311,498
Arts, Entertainment, Accommodation and Food Services	1,382,501	20	487,226
Other Services excluding Government	936,348	14	445,615
Government	2,348,279	15	1,264,438
Households	18,088,493	129	**
Total	**50,166,461**	**319**	**10,062,864**

Notes. * See endnote ix for a description of the calculation of total income impacts. ** Total household impact is the same as total income impact for households.

Table 7 gives input-output estimates of the direct and total value added to the regional economy.

Table 7. Average Annual Value Added Impacts of MWCD Operations and Maintenance

Sector	Direct Value Added	Total Value Added
Agriculture, Forestry, Fisheries	1,107	85,316
Mining	16,988	75,940
Utilities	563,300	939,007
Construction	173	117,818
Manufacturing	136,584	1,600,516
Wholesale	631,693	1,492,962
Retail	315,052	1,693,684
Transportation	7,471	443,153
Information	179,606	586,938
Finance, Insurance and Real Estate	273,989	3,953,677
Professional and Business Services	752,216	2,104,205
Education, Health Care, Social Assistance	64,864	2,608,504
Arts, Entertainment, Accommodation, And Food Service	46,292	763,806
Other Services excluding Government	78,081	562,263
Government	727,856	1,486,718
Households	8,029,368	8,029,368
Total	**11,824,639**	**26,543,873**

The total value added impact of MWCD's $14,308,281 average annual direct expenditure for operations and maintenance over the 2014-2022 period was $26,543,873 (value added multiplier = 2.24). This total value added impact of $26.5 million per year on average represents how much total MWCD expenditures for operations and maintenance benefitted the region even after netting out the costs of intermediate inputs, both from within and from outside the study area.

The MWCD total direct expenditure to the household sector for operations and management is a part of the initial, external shock whose impacts are estimated by the analysis, not a part of the structure of the production functions and supply chains found within the regional economy. Thus, to avoid double-counting, the dollars used in this expenditure are initially excluded from the calculations used to estimate the multipliers. Therefore, to accurately estimate the total income impacts of this expenditure, the value of total direct expenditures to the household sector for operations and maintenance must be added to the sum of total income impacts based upon the multipliers. Accordingly, the total annual income impacts in the study area of the MWCD expenditures for operations and maintenance is $10,062,864 + $8,092,232 = $18,092,232.

5. Discussion & Conclusions

This report analyzed a vast amount of data, some of which was from the Bureau of Economic Analysis and some directly from MWCD. The analysis, which was based upon data about the multitude of interactions that exist between industries within the study region's economic system together with longstanding, widely accepted and applied analytical techniques, provided a significant amount of precise detail about the huge contribution made by MWCD to the study region's economy over the study period. The key finding is that once the multipliers are factored in, the total direct, indirect and induced impacts of the $310,919,843 in combined improvement, operations and maintenance expenditures made to industries, governments and households by the MWCD over this nine-year time period have altogether been in excess of $938,000,000. Thus, there can be no doubt that MWCD has made a significant economic contribution to the regional economy, and that this study has significantly increased the base of available knowledge about this contribution.

Sanitary sewer improvements at Seneca.

6. References

Bjerkholt, O., and Kurz, H.D., (2006). Introduction: the History of Input-Output Analysis, Leontief's Path, and Alternative Tracks. *Economic Systems Research* 18 (4): 331–333.

Daniels, P.L., Lenzen, M., and Kenway, S.J. (2011). The Ins and Outs of Water Use: A Review of Multi-Regional Input-Output Analysis and Water Footprints for Regional Sustainability Analysis and Policy. *Economic Systems Research* 23(4): 353–370.

Hewings, G.J.D. (2020). Regional Input-Output Analysis. Reprint. Edited by Grant Ian Thrall. WVU Research Repository. https://researchrepository.wvu.edu/cgi/viewcontent.cgi?article=1009&context=rri-web-book (last accessed 10/1/2023).

Jackson, R. (1998). "Regionalizing national commodity-by-industry accounts." *Economic Systems Research*, 10(3): 223–238.

Jackson, R. and P. Járosi (2020a). "IO-Snap regionalization." IO-Snap Technical Document 2020 - 01, EconAlyze LLC, Morgantown, WV 26508. http://econalyze.com/TechDocs.

Jackson, R. and P. Járosi (2020b). "Adding foreign imports to IO-Snap regionalization." IO-Snap Technical Document 2020 - 02, EconAlyze LLC, Morgantown, WV 26508. http://econalyze.com/TechDocs.

Jackson, R. (2020). "IO-Snap cross-hauling adjustment." IO-Snap Technical Document 2020 - 03, EconAlyze LLC, Morgantown, WV 26508. http://econalyze.com/TechDocs.

Miernyk, W.H. (2020). The Elements of Input-Output Analysis. Reprint. Edited by Randall Jackson. WVU Research Repository. Original publication date: 1965. https://researchrepository.wvu.edu/cgi/viewcontent.cgi?article=1005&context=rri-web-book (last accessed 10/1/2023)

Miller, R.E. and Blair, P.D. (2009). *Input-Output Analysis: Foundations and Extensions*. Cambridge: Cambridge University Press.

Rose, A. and Miernyk W. (1989) Input–Output Analysis: The First Fifty Years, *Economic Systems Research*, 1:2, 229-272, DOI: 10.1080/09535318900000016

Sun, J.X, Yin, Y.I., Sun, S.K., Wang, Y.B., Yu, X., and Yan, K. (2021). Review on research status of virtual water: The perspective of accounting methods, impact assessment and limitations. *Agricultural Water Management* 243: 06407

West, Guy R. (2020), "Input-Output Analysis in State and Regional Economic Planning." Theory and Methods. 64. https://researchrepository.wvu.edu/rri_iotheorymethods/64 (Last accessed 10/1/2020)

7. Technical Appendix: The Economic Input-Output (IO) Model

The Economic Input-Output (IO) Model is a powerful analytical tool used in economics to study and understand the interdependencies and relationships among various sectors of an economy. This model provides a systematic framework for quantifying the flow of goods, services, and monetary transactions between different sectors and industries within an economy. It is widely employed for a range of purposes, including economic forecasting, policy analysis, and assessing the economic impacts of various events or policy changes.

Here is a more detailed description of the Economic Input-Output Model:

1. **Interconnected Sectors:** At its core, the IO model represents an economy as a complex web of interconnected sectors or industries. Each sector produces goods and services, which are then used as inputs by other sectors. These interdependencies create a network of relationships that can be represented in a matrix format.

2. **Transaction Flows:** The model quantifies the monetary flows between sectors, reflecting how much money each sector spends on inputs from other sectors. This includes intermediate goods and services, as well as final consumption and investment.

3. **Matrix Representation:** The IO model is often presented as an input-output table or matrix, where each row represents a sector, and each column represents a sector. The entries in the matrix indicate the monetary value of transactions from one sector to another. It distinguishes between transactions within the same sector (e.g., a sector purchasing its own products) and transactions between different sectors.

4. **Coefficient Matrix:** An important aspect of the model is the coefficient matrix, which shows the input requirements for each sector to produce a unit of output. This matrix captures the technical relationships between sectors and is crucial for understanding the ripple effects of changes in demand or production within the economy.

Relevant assumptions and definitions in the tables found in this report are as follows.

- The BEA industrial categories used in the analysis are listed in the column labeled “Sector.”

- The columns labeled “Direct Output Impacts by Commodity” and “Direct Output Impacts by Industry” are logs of how the total MWCD expenditures were distributed across the corresponding row’s BEA-code category. In other words, the direct output impacts are exogenously given primary data provided by MWCD and assigned by the EPC team to the BEA and categories listed in the “Sector” column.

- The column labeled “Total Impacts by Industry” is a mathematical product of the input-output model. It gives the sum total of the direct, indirect and induced effects of MWCD spending specifically in the corresponding industry listed in the “Sector” column, as described above.

- The column labeled “Total Employment Impacts” is the multiplicative product of the Total Impact by Industry for the corresponding industry listed in the “Sector” column, and the total number of statewide employees per dollar of output in that industry in Ohio. In other words, it gives and estimate of the direct, indirect and induced number of jobs in the sector listed in the "Sector" column attributable to MWCD expenditures. Employment was measured by numbers of jobs (not FTE).

- The column labeled "Total Income Impacts" gives the multiplicative product, by industry, of the Total Employment Impacts (for the corresponding industry in the "Sector Name" column), and mean statewide compensation per employee in that industry. In other words, it estimates the direct, indirect and induced amount of compensation to regional employees in the sector listed in the "Sector" column attributable to MWCD expenditures.

- The Direct Value Added column gives the increment to value added in the corresponding row industry attributable directly to MWCD expenditures. Value added in a given industry represents an increase in true economic profit within that industry: it is the difference between market value of the products or services provided by that industry and the value of the sum of the inputs to its production. In this research it was estimated by the sum, by industry, of employee compensation (wages, salaries, and benefits), payments to government (indirect business taxes), and gross operating surplus (profit).

- The Total Value Added column gives the direct, indirect and induced value added, which is to say the direct value added after factoring in its multiplier.

- Average compensation equals (the sum of direct compensation impacts) / (the sum of direct employment impacts).

- Employment corresponding to direct-to-household payment value is estimated by (payment to households) / (average compensation).

- Note that the Government industry represents the annual costs of operating the government, not the final demand expenditures (like highway investments) that are a part of government's final demand expenditures.

- Multipliers are ratios of total to direct impacts.

The most used commercial economic input-output (IO) software application, IMPLAN, has gained widespread acceptance. A more recently introduced option is IO-Snap software, developed and distributed by EconAlyze, LLC. Another option, RIMS II, is available from the U.S. Bureau of Economic Analysis (BEA), though it is more generally a source for IO multipliers than a full-featured economic software analysis application, and for this reason it was not selected for use in the analysis presented in this document. Below, we compare IMPLAN and IO-Snap, which have some differences in terms of their features, applications, costs, and user bases.

1. Developer and Availability: Both IMPLAN and IO-Snap are commercial software applications developed and maintained by private companies. IMPLAN is developed and maintained by the Implan Group, LLC. It is widely used in the United States and has recently introduced data and application support for some non-U.S. economies. IO-Snap is developed by EconAlyze LLC, also a private company. Its data and application tools do not support applications outside the U.S. Both applications support subnational regional and national data and tools of analysis.

2. Geographic Coverage: IMPLAN data cover substate geographies such as counties, whereas IO-Snap is primarily geared to U.S., state, and multi-state regions, by default. However, users with sub-state employment and or income data by industry can use IO-Snap to generate corresponding customized geographical regions.

3. Sectoral Detail: Implan data are classified into more than 400 industrial and commodity sectors founded on the U.S. Bureau of Economic Analysis (BEA) benchmark input-output accounts that are published every five years. IO-Snap's sectoral detail is nearly identical to that of the BEA's annual input-output accounts. Note that when all data are known and accurate, more sectoral detail will result in more accurate impacts assessment results. However, as geographical regions become smaller (smaller economies as measured by, e.g., numbers of employees, gross product,etc.), an increasing number of critical parameters are suppressed in published governmental reports and hence the need for imputing missing data increases, often quite dramatically. The ratio of the number of reported data values to the number of imputed data values becomes smaller as region size decreases. Recent preliminary empirical experiments have shown that the uncertainty and error that typically accompany data imputation result in a trade-off between sectoral detail and overall model accuracy; i.e., greater detail may come with a loss of accuracy.

4. User Base: Both IMPLAN and IO-Snap users need at least a minimal foundation in economic principles, but in general, IMPLAN requires less user sophistication than IO-Snap. IO-Snap users often use the application not only to generate information from default analytical features as with IMPLAN, but they can also take advantage of user-friendly support for exporting data to be further processed or used as the foundation for computable general equilibrium, simulation, and other models, or simply for users who prefer to generate the regional accounts and then use supplementary software (e.g., Matlab®) to implement the impact assessment. This latter case was employed for the analysis reported here.

5. Cost: IMPLAN allows for local regional analysis at very granular levels of sectoral detail, corresponding to the 6-digit NAICS level. As previously noted, this can necessitate data imputation or estimation as federal agencies generally do not release data that is highly detailed with respect to both geography and industrial sector so as to ensure that data for individual persons and companies are not disclosed. IMPLAN goes to great lengths to generate and provide highly detailed, disaggregated IO account data at the county and even Zip code level. Generating data at this level of detail comes at a cost that is considerably greater than IO-Snap, which relies on BEA's broader Summary level IO account data that corresponds primarily to the 3-digit NAICS level. The Summary level was sufficient to provide an overview of MWCD's impact on the 18-county regional economy.

For these reasons, IO-Snap was selected as the foundation for this analysis.

Despite their many valuable merits, input-output analyses invariably face some challenges. For all of their power and insight, they rely on certain simplifications and generalizations that may not fully capture the complexity of real-world economic systems. They assume, for example, that economic relationships between industrial sectors are stable over time, which may not always be the case, especially when considering time periods that are as long as from 2014-2022. Additionally, input-output analyses simplify the economy by aggregating sectors and thus may not capture all the nuances of real-world economic dynamics. While they admirably model monetary benefits, they do not consider is what the benefits might have been had the distribution of expenditures been directed differently, such as for an entirely different set of capital projects. Nor do they include intangible benefits such as, for example, the improvements in public health or quality of life in the study area attributable to the MWCD expenditures.

8. Endnotes

1. The 18 counties wholly or partially contained in the MWCD jurisdiction are Ashland, Belmont, Carroll, Coshocton, Guernsey, Harrison, Holmes, Knox, Licking, Morgan, Muskingum, Noble, Richland, Stark, Summit, Tuscarawas, Washington, and Wayne.

2. Jobs from capital expenditures are not permanent while jobs from ongoing O&M are, although O&M jobs may be seasonal or part-time.

3. Gross Output is a measure of sales or revenue, including final and intermediate goods and services.

4. Value Added, or gross domestic product (GDP) by industry, is the difference between Gross Output and the cost of intermediate inputs.

5. See Times Reporter. (2022). MWCD to receive $40 million from Tappan Lake oil and gas lease. https://www.timesreporter.com/story/news/2022/05/23/mwcd-receive-40-million-tappan-lake-oil-and-gas-lease/9853899002/

6. See Energy Policy Center. (2023). Shale Investment Dashboard in Ohio Q1 and Q2 2022. Cleveland State University. https://engagedscholarship.csuohio.edu/urban_facpub/1793

7. See Ohio Auditor of State. (2008-2016). Independent Auditor's Report of the Muskingum Watershed Conservancy District, Tuscarawas County. https://ohioauditor.gov/auditsearch/Search.aspx

8. See Energy Policy Center. (2023). Shale Investment Dashboard in Ohio Q1 and Q2 2022. Cleveland State University. https://engagedscholarship.csuohio.edu/urban_facpub/1793. See also Ohio Auditor of State. (2014-2022). Independent Auditor's Report of the Muskingum Watershed Conservancy District, Tuscarawas County. https://ohioauditor.gov/auditsearch/Search.aspx

9. Muskingum Watershed Conservancy District. (2023). MWCD Invests $5 Million in Environmental Stewardship. https://www.mwcd.org/news/2023/01/27/mwcd-invests-5-million-in-environmental-stewardship

10. A summary of the terms for the lease agreement currently in use can be found on MWCD's website at https://www.mwcd.org/news/2022/05/20/mwcd-negotiates-oil-and-gas-lease-with-encino-energy

11. See Muskingum Watershed Conservancy District. (2022). Annual Report of Operations. https://www.mwcd.org/upload/mwcd_annual_report_2022.pdf

12. Output, or *gross output*, is principally a measure of sales or revenue from production for most industries, while *value added* is the difference between gross output and intermediate inputs and represents the value of labor and capital used in producing gross output. Value added is also measured as the sum of an industry's compensation of employees, taxes on production and imports, less subsidies, and gross operating surplus. See Bureau of Economic Analysis. (2018). What is Gross Output by Industry and How Does It Differ from Gross Domestic Product (or Value Added) by Industry? https://www.bea.gov/help/faq/1197

13. Output multiplier comparisons can be difficult to fully understand because output impacts include double-counting, but income, value added, and employment impacts do not. Output multipliers double count because total output impact includes the value of every input at every step in the supply chain. Demand for an automobile, for example, will generate a total output impact that includes the values of the tires plus the value of the rubber in the tires, the radio plus the value of the wires in the radio, the transmission and engine and the value of the metal stampings and the value of mined metals they are made of, the value of the upholstery, the value of the cloth to make the upholstery, the value of the fertilizer for the cotton in the fabric, etc., etc., etc. Because of this "double-counting", there will be a relatively large output multiplier. It could, however, have a total income effect that is very similar to another industry that has a much lower (or even a higher) output multiplier. One explanation (for a given comparison) would be the fact that the costs of intermediate inputs (per input) used in producing autos are much smaller (therefore generating less income per input) than those of the industry with the smaller output multiplier.

14. Specifically (direct+indirect)/direct is a Type I multiplier. A Type II multiplier is (direct+indirect+induced)/direct. The multipliers reported herein are Type II.

15. The input-output accounts at BEA are a series of related detailed tables showing how industries interact with each other and with the rest of the economy. "Make tables" show the production of commodities by industries. "Use tables" show what industries uses these commodities. "Requirements" tables summarize the full supply chain, including direct and total inputs. Direct requirements tables show the row sector per dollar of input per column sector dollar of output, and its elements are direct input-output coefficients. In a total requirements table, the numerator is the direct and indirect requirements from the row sector per one dollar of final demand for the column industry output, and its elements are direct input-output coefficients. https://www.bea.gov/data/industries/input-output-accounts-data

In this research we employed a "commodity–industry" format, enabling us to account for the fact that an industry may produce more than one commodity (product). This was a major reason for the introduction of this sort of commodity–industry accounting system to the United Nations System of National Accounts in the early 1970s – to explicitly account for "non-characteristic" production such as secondary products and by-products. In addition, data organized in this way are more easily integrated with a broader system of national accounts for the country.

For a more detailed description of these accounts, see: (https://apps.bea.gov/scb/pdf/national/nipa/methpap/mpi1_0907.pdf).

16. See U.S. Bureau of Economic Analysis. (2019). Preview of the 2018 comprehensive update of the industry economic accounts. U.S. Department of Commerce. https://apps.bea.gov/scb/issues/2018/08-august/pdf/0818-industry-tables.pdf

17. Organization for Economic Co-operation and Development. (2023). National accounts: National accounts deflators: Gross domestic product: GDP deflator for United States. Retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/USAGDPDEFAISMEI

18. Secondary production demand refers to the commodities produced within those BEA Industries that produce more than one commodity.

19. Documentation of these methods can be found at https://www.econalyze.com/TechDocs/. Relevant documents are listed individually in the References section.

20. The 18 counties wholly or partially contained in the MWCD jurisdiction are Ashland, Belmont, Carroll, Coshocton, Guernsey, Harrison, Holmes, Knox, Licking, Morgan, Muskingum, Noble, Richland, Stark, Summit, Tuscarawas, Washington, and Wayne.

21. Estimates of total employment impacts (numbers of jobs) are rounded to the nearest whole number for the sake of clarity and coherence.

22. Average compensation {(Sum of direct compensation through 67 industries) / (Sum of direct employment) = $67,887} is based upon Ohio relationships among employees, compensation, and output by industry, emphasizing the sectors that are most directly involved in implementing the improvements.

PCA Since 1916
America's Cement Manufacturers™

Portland Cement Association
200 Massachusetts Ave NW, Suite 200
Washington D.C., 20001
202.408.9494 Fax: 202.408.0877
www.cement.org

November 29, 2023

The Honorable Bill Johnson
Subcommittee on Environment,
Manufacturing, & Critical Materials
Energy & Commerce Committee
Washington, DC 20150

The Honorable Paul Tonko
Subcommittee on Environment,
Manufacturing, & Critical Materials
Energy & Commerce Committee
Washington, DC 20150

Dear Chairman Johnson and Ranking Member Tonko:

The Portland Cement Association (PCA)[1] appreciates you holding the hearing titled, *America Leads the Way: Our History as the Global Leader Reducing Emissions.* This hearing is essential, as an opportunity to share our progress and challenges with Congress, as the cement industry decarbonizes. We hope that you use this hearing to evaluate future federal permitting and regulatory reform along with the investments needed to reduce manufacturing emissions. We also encourage you to hold future hearings on industrial decarbonization. Additionally, as the Committee considers public policies for decarbonization, it should consider the availability of the materials, its resilience, and its ability to protect life.

PCA's members represent the majority of cement production capacity in the United States and serve nearly every congressional district. The cement and concrete industry contribute over $100 billion to the U.S. economy and employs over 600,000 people.

Cement – the principal ingredient in concrete – makes civilization possible. The mixture of portland cement, aggregate, and water makes the building material concrete. Concrete is essential to the modern world. It is used in the pipes and facilities that deliver clean water, to build the ports essential to world trade, to construct mass transit systems connecting people, and in the buildings we work and live in.

Our industry has pledged to become carbon neutral across the cement and concrete value chain by 2050.[2] By way of brief background, cement manufacturers face a unique chemical fact of life. The chemical process required to convert limestone and other raw materials into clinker, the primary ingredient in cement, generates carbon dioxide (CO2) as an unavoidable byproduct during pyro-processing. Currently, roughly 60 percent of all emissions from the cement sector come from these manufacturing process emissions, separate and distinct from energy-related emissions. While the industry expects to make great strides in reducing carbon emissions through measures like using carbon-free fuel/heating technologies and low-carbon/carbon-free raw materials, the full elimination of CO2 generated from raw materials during pyro-processing is not possible. Given this chemical fact of life, the cement industry requires expansive tools and technologies to achieve deep decarbonization.

Cement Blends

Other than water, concrete is the most-used material on the planet, representing about 50% of all manmade materials by mass. The United States uses over 120 million tons of cement each year. Because society produces so much concrete each year, even small changes to its formulation can have dramatic effects on the construction industry's annual carbon footprint—and benefit everyone on the planet.

In the near term, cement manufacturers have developed a modified formula: portland-limestone cement (PLC), a blended cement with a higher limestone content, which results in a product that works the same, measures the same, and performs the same but with a reduction in carbon footprint of 10% on average. Modifying a concrete mix design to replace higher carbon materials with lower carbon ingredients is an effective strategy to reduce its environmental footprint. Whereas the U.S. standard for portland cement allows for up to 5% of clinker to be replaced by limestone, the standard for blended cement allows for 5% to 15% limestone replacement in PLC (Type IL). The same clinker is used to make portland cement and portland-limestone cement, but there is less of it in PLC. And concrete mixes designed with PLCs are compatible with all supplementary cementing materials (SCMs), so when you substitute PLC for ordinary portland cement, you can continue to use all the other materials you use to make concrete for an even greater reduction in carbon footprint. If all cement used in the U.S. in 2019 had been converted to PLC, it would have reduced CO2 emissions by 8.1 million metric tons, which the U.S. EPA says is the equivalent of taking 1.75 million cars off the road for an entire year.

It should be noted that cement, like other building materials, must meet rigorous standards to ensure the safety of the building or infrastructure being constructed. PLC is extensively tested, has proven technology, is readily available through the same supply chain that already successfully serves developers, builders, and contractors.

Alternative Fuels

Regulatory and technical barriers exist for cement plants to use alternative fuels, such as industrial byproducts that otherwise would end up in landfills, including plastics, fabrics/fibers, non-recycled paper and cardboard, tires, and other valuable non-hazardous secondary materials, that will help the industry reach its carbon neutrality goal by 2050. Cement kilns provide an effective and environmentally sound solution that avoids landfilling these materials, benefiting the cement industry and society at large. Since 1990, the industry has reduced its use of traditional fossil fuels by over 15% by using these alternative fuels. Reducing legal barriers to allow kilns to increase usage of these lower-carbon alternative fuels to replace traditional fossil fuels, such as coal and pet coke, can help reduce kiln CO2 combustion emissions.

The U.S. lags well behind the European Union (EU) in its adoption of alternative fuels, which reflects fundamental differences in the regulation of industrial manufacturing, its approach to conserving, recovering, and using secondary materials, and the EU's use of available levers to discourage landfilling and drive carbon reduction.

We see a tremendous opportunity in the U.S. to reduce emissions, via the use of alternative fuels, with the right policies. In the Department of Energy's (DOE) Industrial Decarbonization Roadmap. The agency identified alternative fuels as a pathway for cement manufacturers to reduce their greenhouse gas (GHG) emissions, and the DOE identified needed research on the subject. Among the research it requested for alternative fuels is research on emissions, heating values, carbon content, and contaminant profiles associated with alternative fuels. In the DOE's Industrial Decarbonization Roadmap, DOE also identified the need to catalog fuel mixtures and evaluate economic & GHG reduction benefits and opportunities for economic scale-up of alternative fuels.

The federal government can facilitate additional technical research to analyze the waste and non-hazardous secondary materials streams to confirm that alternative fuels have similar heating values and lower CO2 emissions profiles when compared to traditional fossil fuels. Following such research, we hope that Congress will make pragmatic changes to federal environmental policies that will provide for increased alternative fuel usage while responsibly protecting the environment and enhancing America's energy security.

Carbon Capture Utilization and Storage

The cement industry is facing significant obstacles to implementing carbon capture utilization and storage (CCUS) technologies at its plants. Currently, there are no commercial-scale CCUS installations at any cement plant within the U.S. CCUS cannot be widely implemented at cement plants until there is a clear path to siting and permitting these technologies. Additionally, significant infrastructure investments are required for the capture, compression, storage, and transportation of CO2. Part of that infrastructure will need to supply water and energy for carbon-capture units and associated auxiliary equipment, as well as the energy required for the ultimate delivery of the captured CO2 to its final end-use.

While many promising technologies are under development domestically and overseas, significantly more research and federal funding is needed for CCUS technologies to reach the commercial development stage for the industrial sector, including cement. The cement industry is conducting research on capture technologies, including a variety of solvent, sorbent, and membrane technologies, carbonation, mineralization, calcium (or carbonate) looping, oxyfuel combustion and calcination, cryogenic capture, and algae capture as carbon reduction and removal technologies to hasten the industry's decarbonization efforts. The cement industry is pursuing various potential technologies because each cement plant and cement kiln is different. Their differences include numerous variables, including plant design, emission control requirements, space constraints, water availability, energy availability, and process parameters, each of which will influence the viability of specific carbon removal and reduction technologies. No single off-the-shelf CCUS commercial design or technology will work for every cement plant, and many plants will likely require a combination of capture technologies. It is essential that federal research and funding be directed at multiple technologies so CCUS can feasibly be implemented for the cement industry promptly.

Provided a CCUS technologies can be proven or demonstrated at scale, with substantial research and the implementation of appropriate federal and state policies, CCUS technologies could become scalable within the next ten years.

Given the challenges in decarbonizing the entire cement and concrete value chain, the cement industry will be unable to reach its carbon neutrality goal by 2050 alone. We can only achieve this goal with significant policy support from the federal government to assist with eliminating regulatory hurdles once carbon technologies are commercialized. Needed policy support includes measures to modernize the permitting programs that cover the installation of carbon capture and energy efficiency technologies, carbon transmission infrastructure, and electricity generation. Federal permitting remains an obstacle to the planning, construction, and installation of carbon capture technologies and the infrastructure needed to sequester or utilize the captured carbon. First, there are regulatory obstacles to installing new energy-intensive carbon capture equipment at cement plants and other facilities. The New Source Review (NSR) Program, established under the Clean Air Act Amendments of 1977, presents regulatory barriers for cement facilities to make GHG reduction and energy efficiency improvements. Under the NSR Program, installing CCUS, investing in significant energy efficiency projects, or other major capital investments to reduce GHG emissions at cement facilities result in extended and costly permitting processes and potentially unrealistic emissions and monitoring requirements. The federal government will need to enact policy reforms to reduce these barriers under the NSR Program to ensure that cement plants can install major GHG reduction and energy efficiency technologies, including CCUS technologies, without unnecessary impediments.

Conclusion

All the above-mentioned needs are currently regulated by numerous federal environmental laws with inconsistent guidance, permitting processes, and agency interpretations.

We encourage the Committee to use this hearing to evaluate future federal permitting and regulatory reform along with the investments needed to reduce manufacturing emissions. Such action is necessary to enable the industry to reach its goal of carbon neutrality across the concrete supply chain by 2050. We look forward to working with the Committee on legislation and agency oversight as it considers its next steps. If you have any further questions, please contact me at soneill@cement.org or 202.719.1974.

Sincerely,

Sean O'Neill

Sean O'Neill
Senior Vice President, Government Affairs
Portland Cement Association

Business Roundtable

Strengthening Global Clean Energy Supply Chains

Introduction

Global energy systems are in the midst of a transition to cleaner energy sources and transformative energy technologies, bolstered by a consensus around the need to combat climate change. To lead in this transition, the United States must accelerate the sourcing, manufacture, deployment and scaling up of clean and advanced energy technologies and their associated infrastructure.

However, this accelerating demand for and investment in alternative energy technologies—not only in the United States but around the world—is poised to strain global supply chains and strategic resources. Building a strong foundation for U.S. leadership and fully capitalizing on the potential benefits of Congress' historic investment will require decisive policy and regulatory actions now to establish secure, resilient and efficient clean energy supply chains.

The challenge is significant. Depending on the specific technology, supply chains may be complex, nascent, highly interdependent, vulnerable to unreliable international actors, reliant upon scarce resources and/or constrained by onerous regulatory and permitting requirements. To bolster supply chain resiliency, address potential bottlenecks and position the United States for domestic success and global leadership in the energy transition, policymakers must:

Technologies in Focus

Among the technologies that are critical to the energy transition, Business Roundtable has identified four as facing the most significant near-term supply chain constraints:

- **Solar panels**
- **Transmission grid**
- **Nuclear energy**
- **Clean hydrogen**

Specifically, each of these technologies currently depends on supply chains that are heavily reliant on critical minerals and components with uncertain sources of future supply and/or sourced from foreign entities of concern.

At the same time, Business Roundtable firmly believes that addressing the global climate change and building sustainable and resilient energy systems requires a diverse energy portfolio. This report is not a comprehensive review of alternative energy technologies and resources, or of the policy actions that have a critical role to play in establishing U.S. leadership in the clean energy transition.

More detail and supporting analyses describing the unique and pressing supply chain constraints for solar panels, transmission grid, nuclear energy and clean hydrogen can be found on our website.

Ensure Access To Critical Minerals And Materials

1. Develop and strengthen strategic alliances with friendly, mineral-rich countries (e.g., Indo-Pacific and Latin American countries) to expand and secure access to critical minerals and strategic materials from primary and recycled sources.
2. Support long-term domestic mining, processing and recycling of strategic materials and critical minerals of which the U.S. has sufficient reserves (e.g., lithium, copper, graphite).

Facilitate Competitive Domestic Manufacturing

3. Ensure predictable, consistent regulations and policies related to clean energy development.
4. Ensure promising new technologies receive necessary support to obtain first-mover advantage and secure emerging supply chains longer term (e.g., perovskite-based solar, clean hydrogen and advanced nuclear reactors).
5. Modernize America's workforce development system to scale the supply of skilled workers and equip the next generation with required skills for high-demand jobs.

Support Reliable Component Imports Where Necessary

6. Broaden the geographic eligibility criteria for domestic production incentives to secure long-term access to critical components.

Effectively Deploy And Connect Key Technologies

7. Support ongoing efforts to streamline planning and permitting to facilitate efficient deployment of pivotal clean energy projects (e.g., judicial review reform and prioritization of key projects, including brownfields).

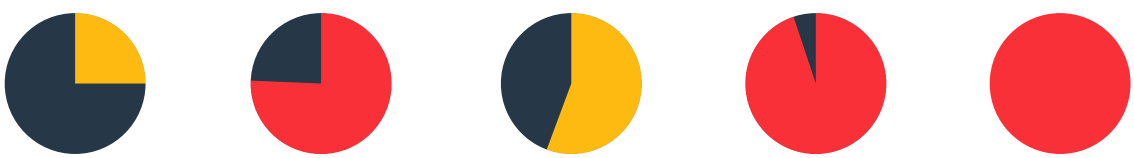
I: Ensure Access To Critical Minerals And Materials

Demand for several critical minerals and materials essential to the clean energy transition is expected to outstrip supply in the short-term, creating significant shortages and increasing prices and volatility. For example, lithium, which is essential for electric vehicles (EVs) and battery storage, is expected to have a 65 percent supply deficit by 2030[1] and has seen its price increase from around $10,000/metric ton (T) in 2020 to over $60,000/T in 2022 before falling to around $20,000/T in 2023.[2,3] And many of the technologies subsidized by Inflation Reduction Act (IRA) and Infrastructure Investment and Jobs Act (IIJA) funding and tax credits will increase demand for copper over the next several decades.

At the same time, limited available mineral supply and headwinds in scaling domestic mining, processing and recycling capabilities have made the United States highly dependent on imports *(see Figure 1)*, often from countries with geopolitical risks and/or substandard environmental and labor practices. For instance, in 2022 China—which controls global mineral processing capabilities in large part due to low labor costs, lagging environmental standards, substantial foreign investments and historical government support[4]—was the leading import source for 17 of the more than 50 mineral commodities for which the United States is more than 50 percent reliant on imports[5].

To effectively secure access to critical minerals and other strategically important materials, the United States must **develop and strengthen strategic trade alliances while supporting domestic mining, processing and recycling.**

Figure 1: **U.S. Reliance On Imports For Key Critical Minerals, Select Uses, Top Supplier (2022)**



>25% Lithium (Li)	76% Cobalt (Co)	56% Nickle (Ni)	>95% Rare Earth Elements (REEs)	100% Natural Graphite (C)
Electric vehicles Battery storage	Electric vehicles Battery storage H2 electrolysis	Electric vehicles Battery storage Solar PV	Electric vehicles Battery storage Wind turbines	Electric vehicles Battery storage H2 electrolysis
Top Supplier: **Argentina**	Top Supplier: **Norway**	Top Supplier: **Canada**	Top Supplier: **China**	Top Supplier: **China**

Note: Top supplier over 2018-2021 | Source: U.S. Department of Energy, U.S. Geological Survey

Recommendations

1. **Develop and strengthen strategic alliances with friendly, mineral-rich countries (e.g., Indo-Pacific and Latin American countries) to expand and secure access to critical minerals from primary and recycled sources.**

   In 2022, the United States was reliant on imports for over 50 percent of its consumption of 43 out of 50 critical minerals—and 100 percent reliant on imports for 12 of these minerals.[6] Growing geopolitical threats and increased demand for clean energy components worldwide threaten U.S. access to future critical mineral imports. Current trade restrictions, including tariffs on refined critical minerals from most countries (e.g., 5 percent ad valorem tax on Rare Earth Elements[7]), reduce cost competitiveness of domestically produced components and further exacerbate the issue.

   High-quality free trade agreements (FTAs) are essential tools for mitigating resource constraints in this area insofar as they reduce tariff barriers, minimize non-tariff barriers such as opaque regulatory requirements and ensure critical minerals are extracted and processed or recovered and recycled in compliance with fully enforceable labor and environmental standards. The Administration, in consultation with Congress, should:

   - **Review existing FTAs** to determine the extent to which they secure access to mining and processing capacity or recycled material supply crucial to the energy transition. **Where existing FTAs prove to be insufficient, the agreements should be reopened and amended** to achieve this objective.
   - **Pursue new, high-standard, enforceable FTAs, including in the Indo-Pacific region,** that contain enforceable market-access commitments, including reduced tariff bindings, clear rules of origin and high-standard investment protections to facilitate the integration of U.S. critical minerals supply chains.
   - **Build and expand pilot trusted trader programs for resource recovery trade** by leveraging ongoing work and models in international forums as well as in bilateral and regional dialogues. Ratify the Basel Convention, which will qualify the United States to receive more recyclable materials from global markets and boost the growth of a domestic recycling industry.

In the interim, while pursuing these FTAs, **policymakers should examine whether additional bilateral or plurilateral critical-minerals-specific agreements** could be negotiated with enforceable market-access commitments, environmental and labor standards, as well as provisions to limit the imposition of regulatory barriers and export restrictions that disrupt trade in this area *(see Figure 2).*

Figure 2: Potential Critical Minerals Trading Partners

These countries present an opportunity for U.S. minerals interests given existing relations, high concentrations of the world's mining production and reserves of key minerals, potential to improve environmental and labor conditions and the ability to combat growing influence from foreign competitors:

		Indonesia		South Africa	Brazil		Philippines	European Union	
	Most Prominent Mineral(s)	Nickel	Copper	Platinum Group Metals	Graphite	REEs	Nickle	Chromium	Cobalt
	Concentration of world production and reserve	~50% mine production ~40% processing	~4% mine production ~3% global reserves	~75% platinum mining ~90% processing	~23% global reserves	~17% global reserves	~10% mining production	~5% mining production	~15% processing
	U.S. Import Reliance	>50%	41%	>50%	100%	>95%	>50%	~75%	~75%
Material Use Cases	Geothermal	✓					✓	✓	
	Solar	✓	✓				✓	✓	
	Wind	✓	✓			✓	✓	✓	
	EVs	✓	✓		✓	✓	✓		✓
	Battery Storage	✓	✓		✓	✓	✓		✓
	Hydro		✓					✓	
	Nuclear	✓	✓				✓	✓	
	H_2 Electrolysis	✓	✓	✓	✓		✓		✓
	Other Considerations	Growing Chinese investment in Indonesian nickle mining and processing over the last decade.	Significant processing capacity expected to come online in 2023.				Ongoing USTDA critical minerals project with Eramen Mineral to support mineral processing standards in Philippines.	Processing is a critical step in the supply chain and is led by China for most mineral commodities (e.g., ~70% of cobalt processing)	

Note: Platinum Group Metals are iridium, osmium, palladium, platinum, rhodium and ruthenium
Source: U.S. Geological Survey, International Renewable Energy Agency, Bank of America Global Research, U.S. Trade and Development Agency, International Energy Agency

2. **Support long-term domestic mining, processing and recycling of strategic materials and critical minerals of which the U.S. has sufficient reserves (e.g., lithium, copper, graphite).**

   Domestic mining and processing capabilities for several minerals have atrophied over the past few decades, largely due to unfavorable market conditions and insufficient policy support. Metals mining in the United States decreased by around 25 percent between 1990 and 2018[8] leaving significant untapped potential in domestic resources of minerals such as lithium, copper and rare earth elements.[9] Improving the U.S. market position and the nation's ability to successfully transition to clean energy is essential.

   The United States has begun implementing policies to incentivize production of a select set of minerals and materials deemed important for national and economic security, based on the U.S. Geological Survey (USGS) list of 50 critical minerals most recently updated in 2022 and the Department of Energy's (DOE) list of critical materials, which also includes materials like silicon and electrical steel. For example, the IRAadvanced energy project credit (U.S.C. § 48C) provides a 30 percent investment credit to qualifying projects, including re-equipping, expanding or establishing facilities for processing, refining or recycling critical minerals and materials as defined by USGS and DOE.[10]

   While ongoing efforts have helped smooth regulatory hurdles (see section IV) and reduce production costs for some minerals, USGS's and DOE's existing criteria for designating minerals and materials as "critical" can fail to capture anticipated demand and omit materials that are pivotal for the energy transition (e.g., copper). The U.S. Department of the Interior, acting through USGS, and DOE should take the following actions to ensure that U.S. companies can harness the potential of domestically available mineral resources and processing operations, including downstream smelting and refining of strategic minerals:

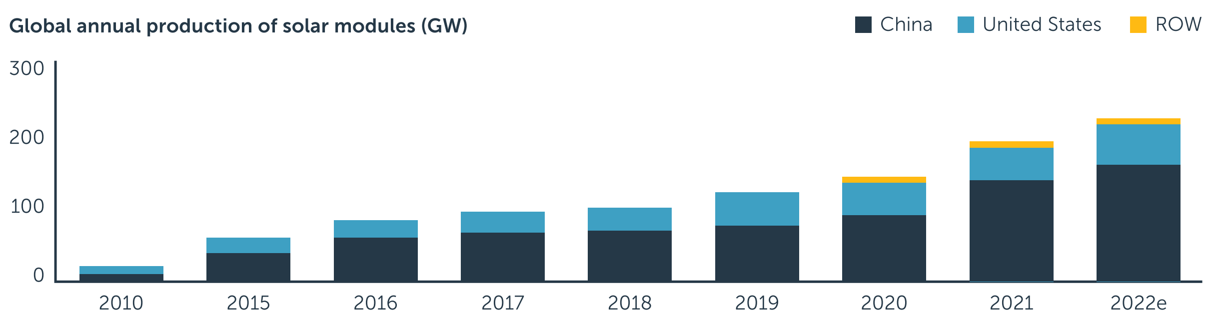
   - **Adjust the standards** used by USGS and DOE to determine mineral and material criticality and ensure both lists accurately reflect the near-term risk of anticipated supply deficits, with ample opportunity for input from stakeholders.
   - **Make official the draft list of critical materials**[11] to enable access to advanced energy project tax credits (U.S.C. § 48C) and DOE grant and loan programs.
   - **Reform the permitting process for domestic mining and processing** to make available more resources in a safe, expeditious and predictable way.
   - **Enhance capacity for critical minerals reclamation and recycling** and support research to enhance recoveries of strategic minerals and develop artificial substitutes that lessen dependence on foreign-sourced critical minerals.

II: Facilitate Competitive Domestic Manufacturing

Over the past few decades, market forces, predatory foreign government practices, dumping and lack of targeted domestic strategies have incentivized many U.S.-domiciled multinational corporations to outsource critical manufacturing capabilities. As a result, the country has fallen behind on innovation and manufacturing for several key technologies—including but not limited to those analyzed in this report—and has seen a significant decline in related domestic skilled labor. For instance, domestic solar wafer and cell manufacturing atrophied by 2020 due to price competition with Chinese companies, which benefitted from structural advantages provided by the Chinese economy and sustained government support *(see Figure 3).*[12,13] In 2010, North America produced 4.6 percent of global solar cells and by 2021 had little to no domestic production.[14]

A predictable policy environment is essential to minimizing risk, particularly for projects with long pay-back periods. A U.S. government strategy that is consistent with U.S. free market dynamics and includes targeted incentives will help the United States continue improving its position as a leader in the energy transition and building a first mover advantage in the new wave of clean energy technologies. The United States must provide long-term certainty for clean energy investment, ensure promising new technologies receive necessary support to obtain first-mover advantage and grow critical talent pools by promoting high-quality training programs.

Figure 3: Chinese Solar Industry Accelerated Under Government Support



China's Share:

2010	2015	2016	2017	2018	2019	2020	2021	2022e
48%	65%	71%	70%	68%	63%	64%	72%	72%

China's policy incentives (non-exhaustive):

- **2008** — Central gov stimulus of **~$2T** bank credits for solar companies.
- **2011** — New feed-in tariffs announced centrally (15-18¢ per kWh).
- **2012** — Anti-dumping duty on high-purity polysilicon imports from US and Korea.
- **2015** — 'Top Runner Program' incentives efficiency for solar farm developers.
- **2021** — Solar pilot mandates installation quotas in select counties by end of 2023.

Source: International Energy Agency

Recommendations

3. **Ensure predictable, consistent regulations and policies related to clean energy development.**

   A predictable and favorable policy environment is essential to achieving U.S. clean energy potential and advancing U.S. competitiveness. A stable policy environment facilitates investment in domestic clean energy industries, including investments in emerging technologies (e.g., High-Assay, Low-Enriched Uranium, or HALEU, fuel for advanced nuclear reactors,[15] clean hydrogen storage[16]) and facilitates rapid adoption of these new technologies. Conversely, legislative and regulatory uncertainty hinders U.S. companies in their ability to execute on already high-risk projects with long payback periods.[17] Congress and the Administration should:

   - **Maintain a favorable policy environment** that will enable efficient deployment of capital towards clean energy projects and help grow domestic industries as they scale to the point of self-sufficiency.
   - Ensure implementation guidance and rulemakings related to existing policies are timely, reflect long project development timelines and preserve eligibility for a broad and diverse suite of projects.

4. **Ensure promising new technologies receive necessary support to obtain first-mover advantage and secure emerging supply chains longer term (e.g., perovskite-based solar, clean hydrogen and advanced nuclear reactors).**

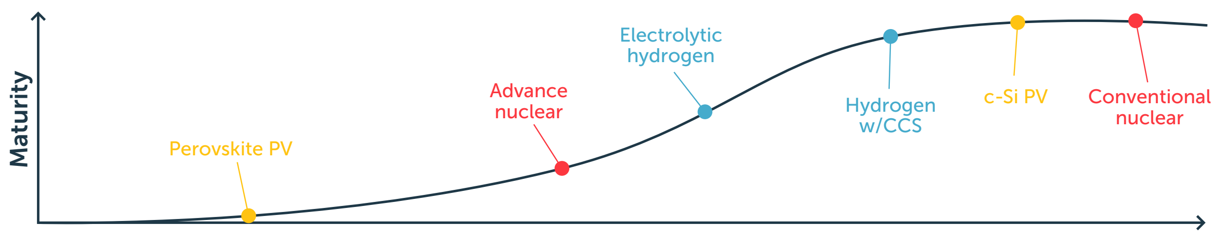
   Along with incentivizing the continued deployment of existing technologies and solutions not yet available at scale, the United States must actively support emerging technologies to solidify its position at the forefront of the new wave of technological innovation.

   Recent legislation,[3] including IIJA, establishes significant funding aimed at accelerating new clean energy technologies. For example, Congress expanded the DOE's Loan Program Office (LPO) in recent legislation, creating significant capacity for the DOE to direct funding to emerging technologies. Historically, however, authorized programs have not always been fully funded. For instance, Congress repeatedly underfunded the National Science Foundation, DOE Office of Science and the National Institute of Standards and Technology, creating a $77 billion gap between funding set out in the 2007 America COMPETES Act and cumulative funding by FY 2021.[18] More recently, while the CHIPS Act[19] created programs and funding to strengthen clean energy research and development (including $8.5 billion to support federal research, development and deployment for advanced nuclear technologies and fusion research), Congress has not fully appropriated funding for these programs.[20,21]

   Where funding is appropriated, it is rarely directed towards advancing and scaling newer technologies with longer investment horizons when more mature counterparts are in the market. Of over $10 billion granted to the LPO for solar projects, for example, no funding has gone to support perovskite, an emerging high-efficiency thin film solar panel technology.[22] Directing a share of funding to more nascent emerging technologies could help create a long-term competitive position relative to countries with substantial history of state-backed commercialization efforts (e.g., China) and solidify the United States' position at the forefront of the energy transition. Congress and the Administration should:

   - **Ensure appropriate authorizations are included** in the next budget to fund existing impactful programs fully (e.g., DOE's Loan Program Office, the CHIPS act).
   - **Direct existing and new funding towards developing, scaling and deploying more nascent emerging technologies,** including perovskite solar, clean hydrogen and advanced nuclear reactors *(see Figure 4).*

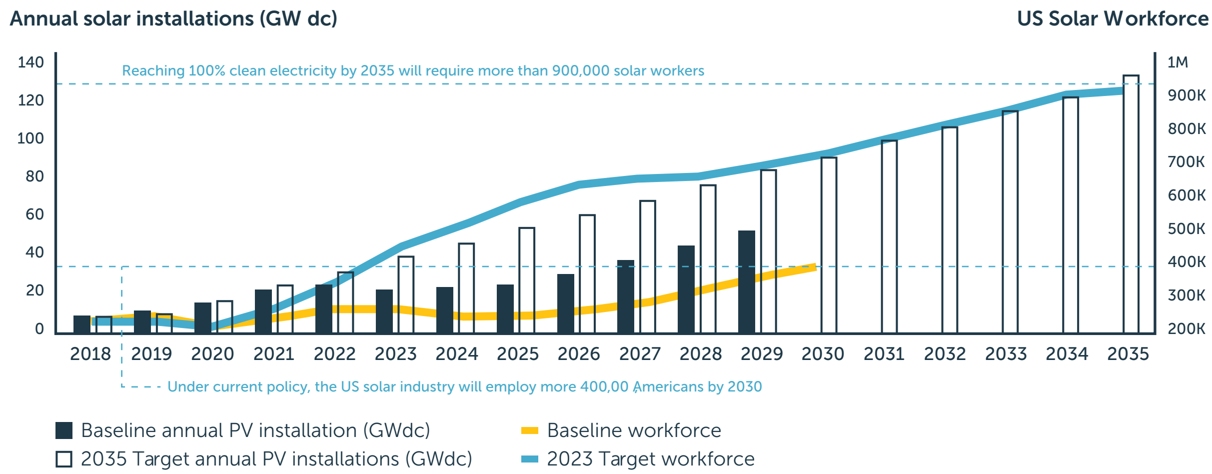
Figure 4: Maturity Levels Of Emerging Technologies Vary, Requiring Different Levels And Types Of Government Support



	Solar	Advance Nuclear	Hydrogen
Challenge	Majority of solar funding is deployed into c-Si PV, with **limited funding going towards R&D** for promising alternatives such as perovskite PV.	Advance nuclear reactors are ready for initial deployment, but risk of significant cost overruns remains a critical barrier to first-movers.	Thus far, guidance for qualification under 45V credit have not been published and some of those being contemplated could threatened this nascent industry's ability to scale; siting and permitting challenges could prevent the timely build-out of necessary supporting infrastructure.
Potential Solution	Allocate/specify existing solar incentives (e.g., LPO loan guarantees, national lab programs) towards **R&D for c-Si alternatives.**	Reduce risk for first-of-a-kind projects, including by authorizing DOE to provide cost overrun insurance above a certain cost threshold.	Publish rules for 45V that incentivize broad deployment of clean hydrogen; address permitting challenges.

5. **Modernize America's workforce development system and employment-based immigration systems to meet employers' needs for skilled workers in high-demand careers.** To sustain a leadership position in the energy transition and effectively meet clean energy demand growth, the United States must rapidly develop and grow its skilled labor pool. For example, the Administration's 100 percent clean energy target and the associated policy support is expected to drive growth in the solar energy industry that will require almost 4 times its current workforce by 2035 *(see Figure 5).*[23]

Figure 5: U.S. Solar Workforce Demand



Source: International Renewable Energy Council

The United States must improve its workforce development system to better prepare workers for in-demand careers and strengthen the country's ability to competitively transition to low-carbon energy. This can be achieved by empowering states to structure workforce systems that meet their economic needs and deliver for workers; promoting high-quality, relevant employer-driven training programs, including apprenticeships, on-the-job training, internships and other forms of work-based learning; and giving workers more freedom and flexibility to get the training they need for fulfilling careers.[24] In particular, the employer-driven training model provides the market with flexibility optimally to align training programs to specific industry needs to address pressing and evolving domestic workforce concerns. Specifically, policymakers should:

- **Revise the Registered Apprenticeship Program,**[25] run by the Department of Labor, to align with evolving workplaces, occupations and career pathways.
- **Modernize the Workforce Innovation and Opportunity Act,**[26] the cornerstone of the public workforce development system, to direct more resources to training programs that meet states' regional workforce needs; to support sector-based partnerships and expand community colleges' and other high-quality providers and workforce partners' ability to work with employers; and to give workers more options to enroll in employer-driven training programs, including by expanding eligible uses of individual training accounts to upskill incumbent workers if their current job is in jeopardy due to technology or automation shifts and removing unnecessary limitations on the use of funds for on-the-job training.
- **Swiftly pass legislation**[27] to expand Pell Grant eligibility to high-quality short-term training programs, increasing the number of students and workers who can afford workforce-oriented, skills-training that leads to in-demand careers.
- **Reform the employment-based immigration system by, for example,** increasing annual limits and eliminating per-country limits, allowing temporary workers to remain in the United States if caught in the backlog and removing barriers to retaining foreign-born graduates of U.S. colleges and universities, to establish a resilient U.S. workforce and build the innovative and globally competitive economy of the future.

III: Support Reliable Component Imports Where Necessary

Securing long-term economically competitive offtake of clean energy components requires cooperation across jurisdictions. Narrow supplier bases for clean energy components put the entire value chain and transition at risk. For example, the shortage of high-voltage direct current (HVDC) converters limits the grid and renewable energy generation transformation underway. Building and expanding capacity in allied countries that have competitive market conditions and manufacturing capabilities will ensure long-term access to key components. To do so, the United States should enact broad eligibility requirements for clean energy tax incentives.

> "We ***can't onshore everything,*** our company and assets are global, and we ***match our supply chain across the globe where there's the right infrastructure, materials and people*** .... We need to ***focus on cost competitiveness.***"
>
> **— Critical Minerals Lead, BRT Member Company**

Recommendations

6. **Broaden the geographic eligibility criteria for domestic production incentives to secure long-term access to critical components.**

   The recently enacted clean energy incentives contain several provisions that incentivize onshoring or near-shoring manufacturing for a specific list of clean energy components. For example, the advanced manufacturing production tax credit (26 U.S.C. § 45X) provides an incentive for eligible components produced ***within the United States.***[28] However, not all components critical to U.S. clean energy buildout are able to be built in these regions or recognized as eligible for the incentives.

   Manufacturing location requirements and inadequate component eligibility will impede U.S. ability to progress as a leader in the energy transition. For example, the advanced manufacturing production tax credit is limited to production of only solar energy components, wind energy components, inverters, qualifying battery components and applicable critical minerals.[29] Geographic limitations in current policy will also hinder U.S. ability to secure access to components such as HVDC converters, which are almost entirely produced abroad, in an economically viable way in the short-term while domestic capabilities are being developed.[30] Adjusting eligibility requirements for both manufacturing locations and qualifying components will help secure long-term access to critical clean energy components from regions with competitive manufacturing conditions. Some eligibility changes can be accomplished by using Treasury guidance to interpret terms like "free trade country" and "eligible components" more broadly. Other provisions, including those that require manufacturing to occur within the United States, require longer-term statutory change. To address these issues, the Treasury Department and other relevant agencies should:

- **Expand the definition of "eligible components"** to include additional clean energy technology inputs and ensure crucial inputs for clean energy infrastructure qualify for tax credits (e.g., permanent magnets for EV motors, HVDC converters).
- **Extend eligible manufacturing locations,** for clean energy tax incentives to U.S. companies manufacturing in, or procuring from, free-trade and other non-comprehensive trade agreement countries (e.g., Japan, EU).[31]

IV: Effectively Deploy And Connect Key Technologies

The United States has invested billions of dollars into clean energy infrastructure over the last decade. Modernizing the electric grid is important to the clean energy transition and can make the grid more resilient and reliable. However, regulatory and jurisdictional complexity and legal delays during the planning and permitting processes have slowed deployment *(see Figure 7)*. To build clean energy infrastructure, attract investments and solidify the United States' position as a leader in the energy transition effectively, Congress and the Administration must **build on recent progress to streamline the planning and permitting processes** while continuing to protect the environment.

Figure 7: Significant Delays In Permitting Causes Major Transmission Grid Backlogs

Major grid projects require permits from local, state and federal governments and agencies before they can break ground. Requirements such as Environmental Impact Studies (EIS) serve an important purpose but are poorly managed and can be more burdensome and time consuming than necessary, with the average EIS alone comprising over 650 pages, taking about 4.5 years to complete and costing over $1 million.

Idaho Power transmission line:

- In 2008, Idaho Power began applying for permits for a **290-mile transmission line** connecting Idaho to Oregon.
- The Bureau of Land Management finished its environmental review **9 years later**, in 2017.
- The project still awaits separate permits from the **EPA** (federal wetlands permit) and **Owyhee County, Idaho.**

Source: Route Fifty, Brookings Institution

Recommendations

7. **Support ongoing efforts to streamline planning and permitting to facilitate efficient deployment of pivotal clean energy projects (e.g., judicial review reform and prioritization of key projects, including brownfields)** Administrative delays, insufficient staffing resources and overly complex review scopes contribute to lengthy delays in federal regulatory reviews and significant clean energy backlogs. For example, from 2010 to 2018, it took an average of 4.5 years to complete an Environmental Impact Study (EIS) and issue a Record of Decision.[32] If implemented appropriately, recent policies including provisions in the IIJA[33] and the Fiscal Responsibility Act,[34] will help speed up clean energy projects.

Key permitting provisions within the Fiscal Responsibility Act41 (June 2023):

- Designates a single ***lead federal agency*** and concurrent reviews.
- Requires a ***single*** environmental review document.
- Requires agencies to evaluate ***foreseeable environmental consequences*** of project proposals.
- Institutes a ***150-page limit*** for Environmental Impact Study (EIS) documents or 300 pages for proposals of exceptional complexity.
- Creates a ***public schedule*** for completion of reviews (e.g., 2-year limit for EIS).
- Requires the Council on Environmental Quality (CEQ) to conduct a study about the potential benefits of ***digitization*** (online portal).
- Commissions FERC to study transfer capabilities and ***interregional connectedness of the grid.***
- Amends the list of ***"covered projects"*** under FAST-41 to include energy storage.

Additional permitting reforms are needed to maximize the impact of government incentives and quickly deploy critical mineral and clean energy infrastructure that will take time to construct and scale up. For instance, the only applicable statute of limitations that applies to all National Environmental Policy Act (NEPA) reviews is the general six-year limit as defined by 28 U.S.C. § 2401;[35] litigation can therefore lead to lengthy court delays or sometimes even entirely block critical additions to U.S. clean energy infrastructure. Suggested improvements for future permitting reform (outlined below) will facilitate U.S. clean energy buildout and bolster domestic clean energy capacity.

Potential improvements for future permitting reform:

- **Litigation reform:**
  - Shorten the statute of limitations to 150 days for legal challenges to federal decisions.
  - Limit standing to qualifying parties (e.g., parties that have participated in the NEPA review process, engaged with communities and affected parties, and have reached out as early as possible).
- **Shorten decision timelines:**
  - Require agencies to issue final decisions within 90 days of completing EIS.
  - For remanded or vacated permitting decisions, require accelerated timelines.
  - Reduce or eliminate redundant reviews by acknowledging state programs.
- **Allocate necessary resources:**
  - Ensure funding (e.g., from IIJA) is deployed to ensure agencies have the tools needed to implement timely permitting programs.
- **Support digitization:**
  - Support implementation of a centralized digital system for agencies to streamline permitting processes (following CEQ completion of study).
  - **Support the Federal Energy Regulatory Commission (FERC) and transmission operator efforts to** improve management of the interconnection application queue and interregional transmission planning, particularly as they relate to adding clean energy projects to the grid.
- **Differentiate and prioritize projects:**
  - Differentiate permitting requirements for projects in areas with ongoing operations and community support (e.g., brownfield sites for mining and processing).
- **Streamline processing requirements:**
  - Remove duplicative requirements across agencies / jurisdictions.

Conclusion

The accelerating transition to clean energy is putting pressure on global supply chains. To maintain and extend its leadership in clean energy manufacturing and the deployment and adoption of clean and advanced energy solutions at scale, the United States must act decisively and strategically to improve the security, resilience and efficiency of energy and technology supply chains.

While many clean energy technologies face obstacles to development and deployment at scale, those examined in this report—solar panels, the transmission grid, nuclear energy and clean hydrogen—face the most significant near-term supply chain issues and require action from Congress and the Administration to:

1. Ensure access to critical minerals and materials by strengthening strategic international alliances and expanding domestic production, processing and recycling capacity;
2. Facilitate competitive domestic manufacturing by ensuring the broad applicability of relevant tax incentives, providing sufficient support to promising new technologies and modernizing the U.S. workforce development system;
3. Support reliable component imports where necessary by securing long-term access to critical components; and
4. Deploy and connect key technologies by streamlining planning and permitting processes.

Addressing global climate change and building sustainable and resilient energy systems will require investments in a diverse suite of technologies and energy sources that are not covered in this report—including carbon capture, wind energy, etc.—each of which faces its own challenges. However, in addition to supporting policies that promote the accelerated deployment of these and other technologies with high emissions reduction potential, Business Roundtable believes the actions outlined in this report are urgently needed to establish a strong foundation for U.S. leadership in alternative energy technologies and a successful clean energy transition.

Endnotes

1. Bank of America Global Research. (2023, March 31). *Delivering the energy transition: where are the bottlenecks and constraints?* https://business.bofa.com/content/dam/flagship/global-research/challenges-to-renewable-energy-transition.pdf
2. S&P Global Market Intelligence. (2022). *Snapshot: Battery Metals Market Outlook.* https://pages.marketintelligence.spglobal.com/rs/565-BDO-100/images/battery-metals-market-outlook-080622.pdf
3. Trading Economics. (2023, October). *Lithium*. https://tradingeconomics.com/commodity/lithium
4. Securing America's Future Energy. (2023, March). *A global race to the top: using transparency to secure critical mineral supply chains.* https://safe2020.wpenginepowered.com/wp-content/uploads/2023/03/SAF-_CritMinReport_v06.3_Spreads_Final.pdf
5. U.S. Geological Survey. (2023). *Mineral commodity summaries 2023: U.S. Geological Survey.* https://doi.org/10.3133/mcs2023
6. U.S. Geological Survey. (2023).
7. U.S. Geological Survey. (2023).
8. National Mining Association. (2020). *Facts about coal and minerals.* https://nma.org/wp-content/uploads/2016/11/factbook2020.pdf
9. U.S. Geological Survey. (2023).
10. Cornell Law School Legal Information Institute. (2023). *26 U.S. Code § 48C - Qualifying advanced energy project credit.* https://www.law.cornell.edu/uscode/text/26/48C
11. Department of Energy. (2023). *What are critical materials and critical minerals?* https://www.energy.gov/cmm/what-are-critical-materials-and-critical-minerals#:~:text=Critical%20materials%20for%20energy%3A%20aluminum,%2C%20silicon%2C%20and%20silicon%20carbide
12. International Energy Agency. (2022, August). *Special Report on Solar PV Global Supply Chains.* https://iea.blob.core.windows.net/assets/d2ee601d-6b1a-4cd2-a0e8-db02dc64332c/SpecialReportonSolarPVGlobalSupplyChains.pdf
13. China Focus. (2021, February 16). *Solar Energy in China: The Past, Present, and Future.* https://chinafocus.ucsd.edu/2021/02/16/solar-energy-in-china-the-past-present-and-future/
14. International Energy Agency. (2022, August).
15. U.S. Department of Energy. (2020, April 7). *What is High-Assay Low-Enriched Uranium (HALEU)?* https://www.energy.gov/ne/articles/what-high-assay-low-enriched-uranium-haleu
16. Department of Energy. (2022, June). *DOE Announces First Loan Guarantee for a Clean Energy Project in Nearly a Decade.* https://www.energy.gov/articles/doe-announces-first-loan-guarantee-clean-energy-project-nearly-decade
17. S&P Global. (2022, September 29). *US green hydrogen costs to reach sub-zero under IRA; longer-term price impacts remain uncertain.* https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/092922-us-green-hydrogen-costs-to-reach-sub-zero-under-ira-longer-term-price-impacts-remain-uncertain
18. American Association for the Advancement of Science. (2022, February 22). *Analysis: As Congress Considers COMPETES, How Short Are We From The Old COMPETS?.* https://www.aaas.org/sites/default/files/2022-02/AAAS%20COMPETES%20Shortfalls%20Feb%202022_0.pdf
19. U.S. Congress. (2022, August 9). *H.R.4346 - Chips and Science Act.* https://www.congress.gov/bill/117th-congress/house-bill/4346/text
20. New York Times. (2023, May 30). *CHIPS Act Funding for Science and Research Falls Short.* https://www.nytimes.com/2023/05/30/us/politics/chips-act-science-funding.html
21. The Brookings Institute. (2023, May 17). *The bold vision of the CHIPS and Science Act isn't getting the funding it needs.* https://www.brookings.edu/articles/the-bold-vision-of-the-chips-and-science-act-isnt-getting-the-funding-it-needs/
22. U.S. Department of Energy. (2023, June). *Loan Programs Office Portfolio Projects.* https://www.energy.gov/lpo/portfolio-projects

Endnotes

23. Interstate Renewable Energy Council. (2021, May 6). *Solar Jobs Support 231,000 Families, Must Grow 4X to Reach Biden's Clean Energy Target.* https://irecusa.org/blog/workforce-development-training/solar-jobs-support-231000-families-must-grow-4x-to-reach-bidens-clean-energy-target/

24. https://s3.amazonaws.com/brt.org/Modernize-America%27sWorkforceDevelopmentSystem.pdf

25. U.S. Department of Labor. (2023). *Registered Apprenticeship Program.* https://www.apprenticeship.gov/employers/registered-apprenticeship-program

26. U.S. Congress. (2014, July 22). *H.R.803 - Workforce Innovation and Opportunity Act.* https://www.congress.gov/bill/113th-congress/house-bill/803/text

27. U.S. Congress. (2023, January 31). *S.161 - JOBS Act of 2023.* https://www.congress.gov/bill/118th-congress/senate-bill/161#:~:text=Introduced%20in%20Senate%20(01%2F31%2F2023)&text=This%20bill%20expands%20student%20eligibility,Training%20Federal%20Pell%-20Grant%20program.

28. Cornell Law School Legal Information Institute. (2023). *26 U.S. Code § 45X - Advanced manufacturing production credit.* https://www.law.cornell.edu/uscode/text/26/45X

29. U.S. Federal Register. (2023, April 17). Section 30D New Clean Vehicle Credit. https://www.federalregister.gov/documents/2023/04/17/2023-06822/section-30d-newclean-vehicle-credit

30. Market participant interview with Vice President at Invenergy

31. U.S. Congress. (2014, July 22). *H.R.803 - Workforce Innovation and Opportunity Act.*

32. Council on Environmental Quality. (2020, July 16). *Update to the regulations implementing the procedural provisions of the National Environmental Policy Act.* https://www.regulations.gov/document/CEQ-2019-0003-720632

33. U.S. Congress. (2021, November 15). *H.R.3684 - Infrastructure Investment and Jobs Act.* https://www.congress.gov/bill/117th-congress/house-bill/3684/text/pl

34. U.S. Congress. (2023, June 3). *H.R.3746 - Fiscal Responsibility Act of 2023.* https://www.congress.gov/bill/118th-congress/house-bill/3746/text

35. Cornell Law School Legal Information Institute. (2023). *28 U.S. Code § 2401 - Time for commencing action against United States.* https://www.law.cornell.edu/uscode/text/26/30D

Oil and gas industry faces moment of truth – and opportunity to adapt – as c

News
23 November 2023

Producers must choose between contributing to a deepening climate crisis or becoming part of the solution by embracing the shift to clean energy, IEA special report says

Oil and gas producers face pivotal choices about their role in the global energy system amid a worsening climate crisis fuelled in large part by their core products, according to a major new special report from the IEA that shows how the industry can take a more responsible approach and contribute positively to the new energy economy.

The Oil and Gas Industry in Net Zero Transitions analyses the implications and opportunities for the industry that would arise from stronger international efforts to reach energy and climate targets. Released ahead of the COP28 climate summit in Dubai, the special report sets out what the global oil and gas sector would need to do to align its operations with the goals of the Paris Agreement.

Even under today's policy settings, global demand for both oil and gas is set to peak by 2030, according to the latest IEA projections. Stronger action to tackle climate change would mean clear declines in demand for both fuels. If governments deliver in full on their national energy and climate pledges, demand would fall 45% below today's level by 2050. In a pathway to reaching net zero emissions by mid-century, which is necessary to keep the goal of limiting global warming to 1.5 °C within reach, oil and gas use would decline by more than 75% by 2050.

Yet the oil and gas sector – which provides more than half of global energy supply and employs nearly 12 million workers worldwide – has been a marginal force at best in transitioning to a clean energy system, according to the report. Oil and gas companies currently account for just 1% of clean energy investment globally – and 60% of that comes from just four companies.

"The oil and gas industry is facing a moment of truth at COP28 in Dubai. With the world suffering the impacts of a worsening climate crisis, continuing with business as usual is neither socially nor environmentally responsible," said **IEA Executive Director Fatih Birol**. "Oil and gas producers around the world need to make profound decisions about their future place in the global energy sector. The industry needs to commit to genuinely helping the world meet its energy needs and climate goals – which means letting go of the illusion that implausibly large amounts of carbon capture are the solution. This special report shows a fair and feasible way forward in which oil and gas companies take a real stake in the clean energy economy while helping the world avoid the most severe impacts of climate change."

The global oil and gas industry encompasses a large and diverse range of players – from small, specialised operators to huge national oil companies. Attention often focuses on the role of the private sector majors, but they own less than 13% of global oil and gas production and reserves.

Every company's transition strategy can and should include a plan to reduce emissions from its own operations, according to the report. The production, transport and processing of oil and gas results in nearly 15% of global energy-related greenhouse emissions – equal to all energy-related greenhouse gas emissions from the United States. As things stand, companies with targets to reduce their own emissions account for less than half of global oil and gas output.

To align with a 1.5 °C scenario, the industry's own emissions need to decline by 60% by 2030. The emissions intensity of oil and gas producers with the highest emissions is currently five-to-ten times above those with the lowest, showing the vast potential for improvements. Furthermore, strategies to reduce emissions from methane – which accounts for half of the total emissions from oil and gas operations – are well-known and can typically be pursued at low cost.

While oil and gas production is vastly lower in transitions to net zero emissions, it will not disappear – even in a 1.5 °C scenario. Some investment in oil and gas supply is needed to ensure the security of energy supply and provide fuel for sectors in which emissions are harder to abate, according to the report. Yet not every oil and gas company will be able to maintain output – requiring consumers to send clear signals on their direction and speed of travel so that producers can make informed decisions on future spending.

The USD 800 billion currently invested in the oil and gas sector each year is double what is required in 2030 on a pathway that limits warming to 1.5 °C. In that scenario, declines in demand are sufficiently steep that no new long-lead-time conventional oil and gas projects are needed. Some existing oil and gas production would even need to be shut in.

In transitions to net zero, oil and gas is set to become a less profitable and riskier business over time. The report's analysis finds that the current valuation of private oil and gas companies could fall by 25% from USD 6 trillion today if all national energy and climate goals are reached, and by up to 60% if the world gets on track to limit global warming to 1.5 °C.

Opportunities lie ahead despite these challenges. The report finds that the oil and gas sector is well placed to scale up some crucial technologies for clean energy transitions. In fact, some 30% of the energy consumed in 2050 in a decarbonised energy system comes from technologies that could benefit from the industry's skills and resources – including hydrogen, carbon capture, offshore wind and liquid biofuels.

However, this would require a step-change in how the sector allocates its financial resources. The oil and gas industry invested around USD 20 billion in clean energy in 2022, or roughly 2.5% of its total capital spending. The report finds that producers looking to align with the aims of the Paris Agreement would need to put 50% of their capital expenditures towards clean energy projects by 2030, on top of the investment required to reduce emissions from their own operations.

The report also notes that carbon capture, currently the linchpin of many firms' transition strategies, cannot be used to maintain the status quo. If oil and natural gas consumption were to evolve as projected under today's policy settings, limiting the temperature rise to 1.5 °C would require an entirely inconceivable 32 billion tonnes of carbon captured for utilisation or storage by 2050, including 23 billion tonnes via direct air capture. The amount of electricity needed to power these technologies would be greater than the entire world's electricity demand today.

"The fossil fuel sector must make tough decisions now, and their choices will have consequences for decades to come," Dr Birol said. "Clean energy progress will continue with or without oil and gas producers. However, the journey to net zero emissions will be more costly, and harder to navigate, if the sector is not on board."

Fuel report

The Oil and Gas Industry in Net Zero Transitions

November 2023

Read the report

The report sets out a fair and feasible way forward in which oil and gas companies and producer economies take a real stake in the clean energy economy while helping the world avoid the most severe impacts of climate change.

Explore report

Latest news

All news

New policy and business approaches are needed to support scaling up of CCUS to help reach net zero goals

News — 27 November 2023

Latest update on clean energy technology manufacturing shows a mixed outlook for key technologies

News — 24 November 2023

IEA convenes EU4Energy forum on sustainable transport policy as momentum grows for electric vehicles and low-emissic

News — 24 November 2023

Leading international figures discuss clean energy labour issues with IEA Executive Director ahead of COP28

News — 23 November 2023

U.S. and China Agree to Displace Fossil Fuels by Ramping Up Renewables

The climate agreement between the two countries is seen as a bright spot as President Biden prepares to meet President Xi Jinping.

By Lisa Friedman

Nov. 14, 2023

The United States and China, the world's two largest climate polluters, have agreed to jointly tackle global warming by ramping up wind, solar and other renewable energy with the goal of displacing fossil fuels.

The announcement comes as President Biden prepares to meet Wednesday with President Xi Jinping of China for their first face-to-face discussion in a year. The climate agreement could emerge as a bright spot in talks that are likely to focus on sensitive topics including Taiwan, the war in Ukraine and the war between Israel and Hamas.

The statements of cooperation released separately by the United States and China on Tuesday do not include a promise by China to phase out its heavy use of coal, the dirtiest fossil fuel, or to stop permitting and building new coal plants. That has been a sticking point for the United States in months of discussions with Beijing on climate change.

But both countries agreed to "pursue efforts to triple renewable energy capacity globally by 2030." That growth should reach levels high enough "so as to accelerate the substitution for coal, oil and gas generation," the agreement says. Both countries anticipate "meaningful absolute power sector emission reduction" in this decade, it says. That appears to be the first time China has agreed to specific emissions targets in any part of its economy.

The agreement comes two weeks before representatives from nearly 200 countries converge in Dubai as part of the United Nations climate talks known as COP28. The United States and China have an outsize role to play there as nations debate whether to phase out fossil fuel.

"This lays the foundation for the negotiations in Dubai," said David Sandalow, a veteran of the

Clinton and Obama administrations who is now a fellow at Columbia University's Center on Global Energy Policy. "It sends a strong signal to other countries that this language works, and more broadly that differences can be overcome."

The agreement does not specify how China will push fossil fuels off its electricity grid. While the United States has displaced some of its fossil fuels by increasing solar and wind power, China has been building more renewable energy than any other country but at the same time has also been constructing new coal-fired power plants.

Still, many of those Chinese coal-fired plants are expected to operate at less than full capacity and the International Energy Agency predicted last month that China's use of coal will drop in the next several years, and possibly as soon as next year.

An analysis by CarbonBrief, a United Kingdom-based energy publication, found that China's emissions are likely to fall next year, after they had rebounded from a decline because of coronavirus restrictions. That is in part because of "record installations of low-carbon electricity" that the analysis found could be enough to meet rising electricity demand.

Mr. Sandalow said displacing fossil fuels as described in the U.S.-China agreement would allow the countries to share knowledge as they both work to add more renewable power to their electric grids and invest in energy storage and better transmission.

"This is the nature of diplomatic statements, they're not binding legal documents but statements of intention," Mr. Sandalow said. But he added, "In my experience, neither the U.S. government nor the Chinese government make high-profile statements like this unless there are serious plans to implement the agreement."

Earlier this month, John Kerry, Mr. Biden's climate envoy, met with his Chinese counterpart, Xie Zhenhua, at the Sunnylands estate in California to lay the groundwork for the agreement announced late Tuesday.

"The United States and China recognize that the climate crisis has increasingly affected countries around the world," the Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis says.

"Both countries stress the importance of COP 28 in responding meaningfully to the climate crisis during this critical decade and beyond" and pledge in the statement "to rise up to one of the greatest challenges of our time for present and future generations of humankind."

As part of the deal, China agreed to set reduction targets for all greenhouse gas emissions. That is significant because the current Chinese climate goal addresses only carbon dioxide, leaving out methane, nitrous oxide and other gases that are acting as a blanket around the planet.

Methane spews from oil and gas operations as well as coal mining and can be 80 times as potent as a greenhouse gas as carbon dioxide in the short term. Greenhouse gases other than carbon dioxide account for a fifth of China's emissions. Methane makes up about half of that, and other gases like hydrofluorocarbons used in refrigeration and nitrous oxide account for the rest.

The Chinese government released a long-awaited blueprint last week for addressing methane, but analysts dismissed it as toothless because it lacked targets for emissions reductions.

The Sunnylands agreement also lacks targets but says the two countries will work together to set them.

China has refused to join the Global Methane Pledge, an agreement among more than 150 nations, led by the United States and Europe, that promises to collectively reduce emissions by 30 percent by 2030.

The United States and China also agreed that in the next set of climate pledges — which nations are supposed to put forward in 2025 — China will set emissions reduction targets across its economy. Its current pledge calls for carbon dioxide emissions to peak before 2030 but does not specify how high they might go before the curve begins to bend or specify by how much it might slash emissions.

President Xi has also pledged that China will become carbon neutral by 2060, meaning it will produce no more carbon emissions than it can offset.

Manish Bapna, president of the Natural Resources Defense Council, an environmental group, praised the U.S.-China agreement and called it "a foundation of ambition" ahead of the U.N. climate summit in Dubai.

"This sends a powerful message of cooperation on the existential challenge of our time," Mr. Bapna said. "What's important now is that both countries make good on today's pledge."

The deal is the product of months of negotiations between Mr. Kerry, 79, and Mr. Xie, 73, friends and sparring partners on climate for more than 25 years. Both left retirement to become climate envoys for their countries and have advocated within their governments for diplomacy on climate change. Mr. Xie, who suffered a stroke last year, is expected to retire after the U.N. summit in Dubai.

Climate negotiations between John Kerry and Xie Zhenhua failed during their meeting last July in Beijing. Valerie Volcovici/Reuters

Their negotiations came to a standstill in 2022 after Nancy Pelosi, then the House speaker, traveled to Taiwan, a move seen as provocative by Beijing. Then, early this year, an American fighter jet shot down a Chinese spy balloon that had floated over the continental United States.

In July, amid efforts by the Biden administration to improve ties, Mr. Kerry traveled to Beijing.

That effort did not end in success. Mr. Xi took the opportunity of Mr. Kerry's visit to deliver a speech declaring that China would never be "swayed by others" on its climate goals.

Still, Mr. Kerry said optimistically at the time that "we set the stage" for a deal.

When it comes to climate change, no relationship is as important as the one between the United States and China.

The United States, the biggest climate polluter in history, and China, the current largest polluter, together account for 38 percent of the world's greenhouse gases.

That means the willingness of the two countries to urgently slash emissions will essentially determine whether nations can limit the average global temperature increase to 1.5 degrees Celsius above preindustrial levels.

That's the threshold beyond which scientists say increasingly severe wildfires, floods, heat and drought will outpace humanity's ability to adapt. The planet has already warmed 1.2 degrees.

But neither the United States nor China will act rapidly unless the other does. Both nations are taking steps to tackle emissions, but hard-liners in each country argue the other is not doing enough, and each country has cast the other's climate promises as insincere.

While the United States has reduced its emissions, Chinese officials have said the American goal of cutting its pollution at least 50 percent from 2005 levels by the end of this decade is inadequate, and some officials have questioned whether the United States can even meet it.

Leaders in China also are acutely aware of the partisan divide in the America on climate change and have little confidence that a future administration would keep promises made by Mr. Biden. Most Republican presidential candidates refuse to acknowledge the established science of climate change, and the front-runner, Donald Trump, has promised to halt climate action and encourage more oil drilling, gas fracking and coal mining.

American lawmakers, on the other hand, note that China's emissions continue to grow and that the country has so far only promised to hit a peak sometime before 2030 and then maintain a plateau before dropping. That's unacceptable for most members of Congress, who believe that China, the world's second largest economy, should be moving at a pace similar to that of the United States.

The Chinese government issued a plan on Nov. 10 to pay large annual bonuses to electric utilities to keep coal-fired capacity available for surges in power demand, even if it is seldom used. Mr. Xi has long emphasized energy security and self-reliance.

That emphasis increased after a 2021 heat wave coincided with a shutdown of many coal-fired power plants. Blackouts ensued in many cities, with office workers being forced to flee down long flights of stairs and with one chemical factory blowing up, injuring dozens of workers.

Keith Bradsher contributed reporting from Beijing.

***A correction was made on Nov. 15, 2023**: Because of an editing error, an earlier version of this article misstated the potency of methane compared with carbon dioxide. Methane can be 80 times as potent as carbon dioxide in the short term, not 80 percent more potent.*

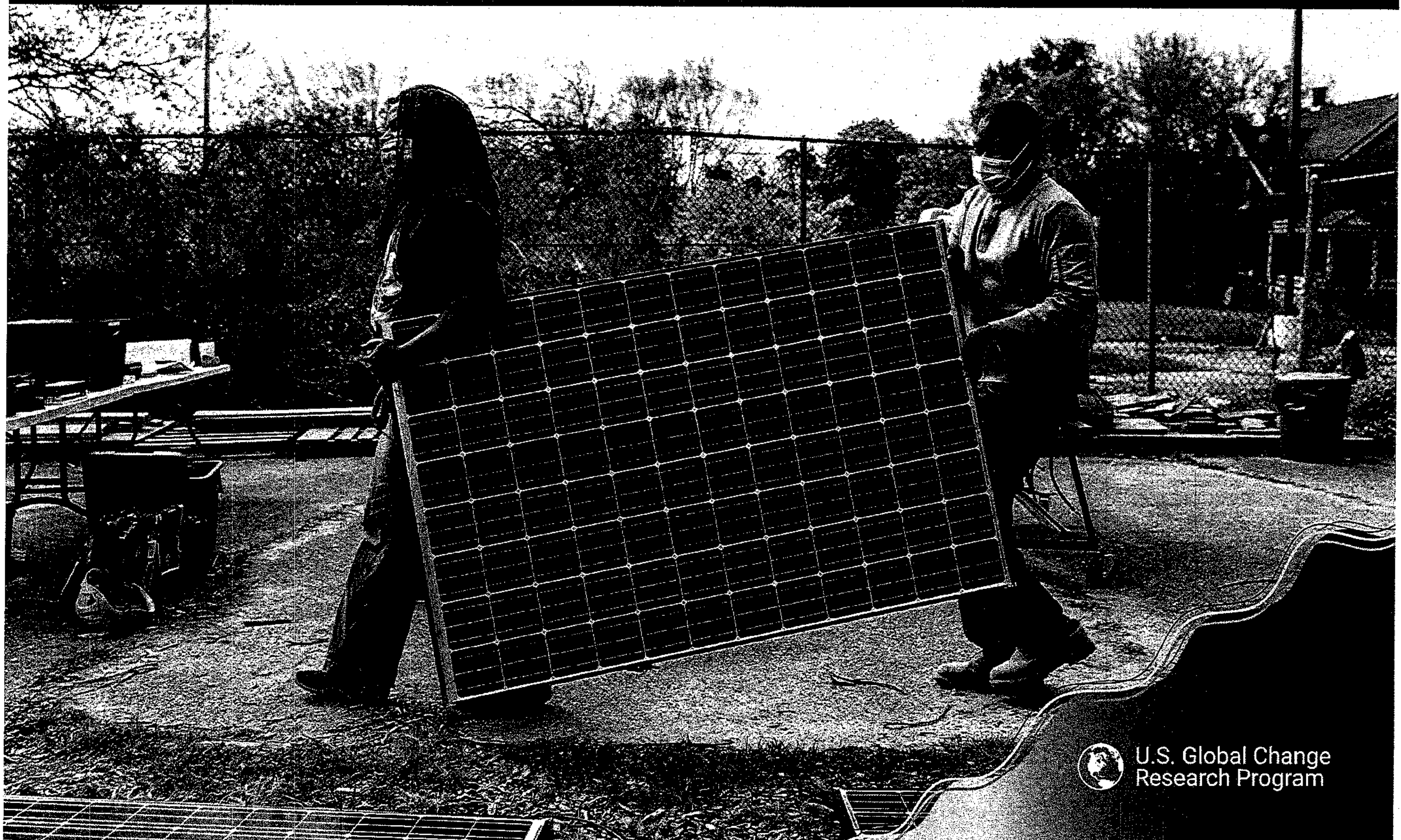
When we learn of a mistake, we acknowledge it with a correction. If you spot an error, please let us know at nytnews@nytimes.com. Learn more

Lisa Friedman reports on federal climate and environmental policy from Washington. She has broken multiple stories about the Trump administration's efforts to repeal climate change regulations and limit the use of science in policymaking. More about Lisa Friedman

A version of this article appears in print on , Section A, Page 11 of the New York edition with the headline: U.S. and China Agree to Jointly Ramp Up Renewable Energy

Overview: Understanding Risks, Impacts, and Responses

Fifth National Climate Assessment



U.S. Global Change Research Program

Chapter 1. Overview: Understanding Risks, Impacts, and Responses

Authors and Contributors

Federal Coordinating Lead Author
Allison R. Crimmins, US Global Change Research Program

Chapter Lead Author
Alexa K. Jay, US Global Change Research Program / ICF

Chapter Authors
Christopher W. Avery, US Global Change Research Program / ICF
Travis A. Dahl, US Army Corps of Engineers
Rebecca S. Dodder, US Environmental Protection Agency
Benjamin D. Hamlington, NASA Jet Propulsion Laboratory
Allyza Lustig, US Global Change Research Program / ICF
Kate Marvel, Project Drawdown
Pablo A. Méndez-Lazaro, University of Puerto Rico
Mark S. Osler, National Oceanic and Atmospheric Administration
Adam Terando, US Geological Survey
Emily S. Weeks, US Agency for International Development
Ariela Zycherman, NOAA Climate Program Office

Review Editor
Emily K. Laidlaw, Laidlaw Scientific

Recommended Citation
Jay, A.K., A.R. Crimmins, C.W. Avery, T.A. Dahl, R.S. Dodder, B.D. Hamlington, A. Lustig, K. Marvel, P.A. Méndez-Lazaro, M.S. Osler, A. Terando, E.S. Weeks, and A. Zycherman, 2023: Ch. 1. Overview: Understanding risks, impacts, and responses. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. https://doi.org/10.7930/NCA5.2023.CH1

Tammy West

The Fifth National Climate Assessment documents observed and projected vulnerabilities, risks, and impacts associated with climate change across the United States and provides examples of response actions underway in many communities. This Overview presents highlights from the Assessment, providing summary findings and a synthesis of material from the underlying chapters. Curly brackets indicate cross-references to full chapters (e.g., {Ch. 2}), Key Messages (e.g., {2.1}), figures (e.g., {Figure 32.8}), and other text elements.

Table of Contents

Ellen Anderson

Margaret Plumley

How the United States Is Addressing Climate Change

The effects of human-caused climate change are already far-reaching and worsening across every region of the United States. Rapidly reducing greenhouse gas emissions can limit future warming and associated increases in many risks. Across the country, efforts to adapt to climate change and reduce emissions have expanded since 2018, and US emissions have fallen since peaking in 2007. However, without deeper cuts in global net greenhouse gas emissions and accelerated adaptation efforts, severe climate risks to the United States will continue to grow.

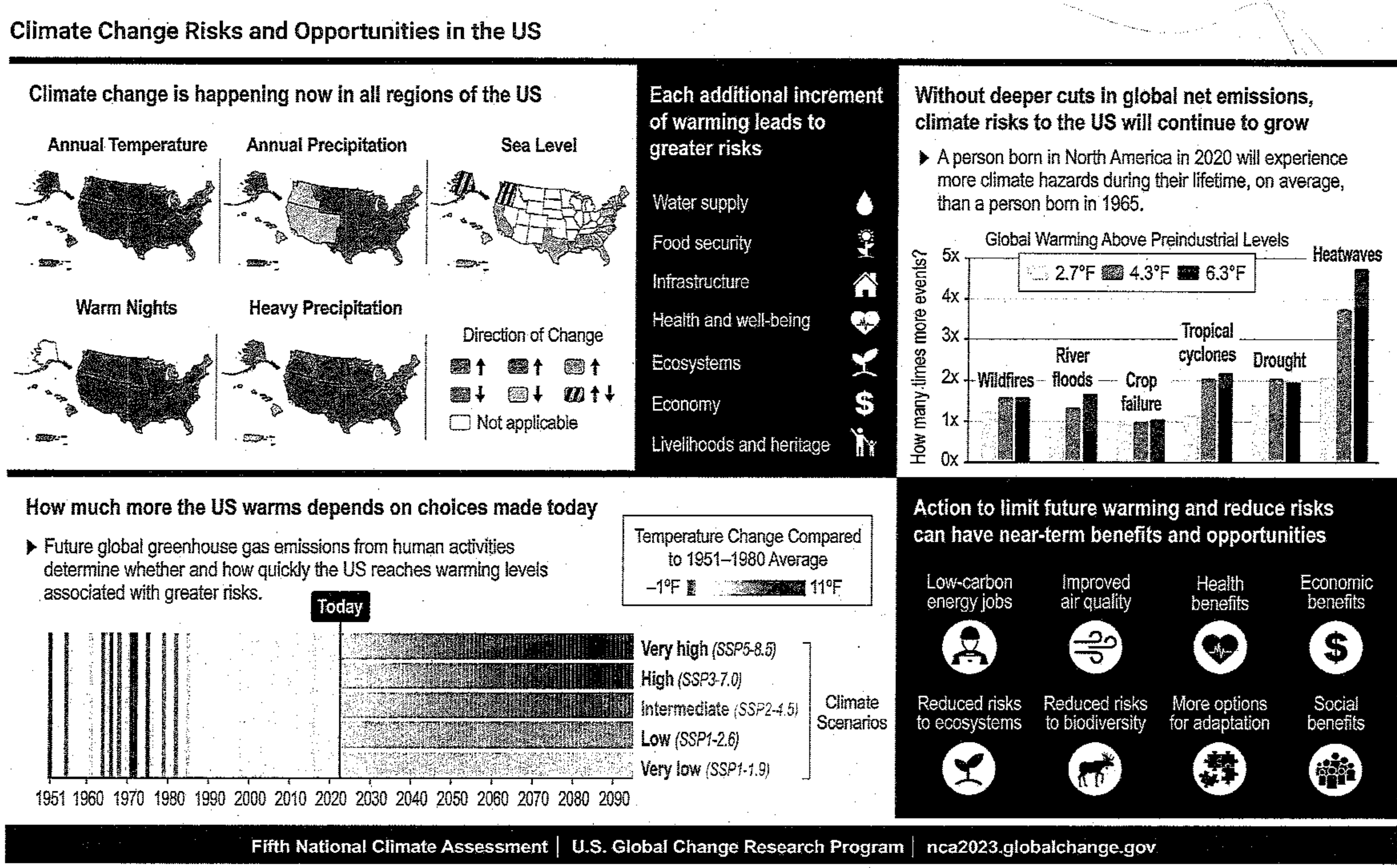
Future climate change impacts depend on choices made today

The more the planet warms, the greater the impacts. Without rapid and deep reductions in global greenhouse gas emissions from human activities, the risks of accelerating sea level rise, intensifying extreme weather, and other harmful climate impacts will continue to grow. Each additional increment of warming is expected to lead to more damage and greater economic losses compared to previous increments of warming, while the risk of catastrophic or unforeseen consequences also increases. {2.3, 19.1}

However, this also means that each increment of warming that the world avoids—through actions that cut emissions or remove carbon dioxide (CO_2) from the atmosphere—reduces the risks and harmful impacts of climate change. While there are still uncertainties about how the planet will react to rapid warming, the degree to which climate change will continue to worsen is largely in human hands. {2.3, 3.4}

In addition to reducing risks to future generations, rapid emissions cuts are expected to have immediate health and economic benefits (Figure 1.1). At the national scale, the benefits of deep emissions cuts for current and future generations are expected to far outweigh the costs. {2.1, 2.3, 13.3, 14.5, 15.3, 32.4; Ch. 2, Introduction}

Taelyn B.



Climate change presents risks while action to limit warming and reduce risks presents opportunities for the US.

Figure 1.1. (**top left**) Changes in multiple aspects of climate are apparent in every US region. The five maps present observed changes for five temperature, precipitation, and sea level rise metrics: 1) warming is apparent in every region (based on changes in annual average temperature in 2002–2021 compared to the 1901–1960 average for the contiguous United States, Hawai'i, and Puerto Rico and to 1925–1960 for Alaska); 2) the number of warm nights per year (days with minimum temperatures at or above 70°F in 2002–2021 compared to 1901–1960) is increasing everywhere except the Northern Great Plains, where they have decreased, and in Alaska, where nights above 70°F are not common; 3) average annual precipitation is increasing in most regions, except in the Northwest, Southwest, and Hawai'i, where precipitation has decreased (same time periods as annual average temperature); 4) heavy precipitation events are increasing everywhere except Hawai'i and the US Caribbean, where there has been a decrease (trends over the period 1958–2021); and 5) relative sea levels are increasing along much of the US coast except in Oregon, Washington, and Alaska, where there is a mix of both increases and decreases (trends over 1990–2020). {2.2, 9.1; Figures 2.4, 2.5, 2.7, 2.8}

(**top center**) Every fraction of a degree of additional warming will lead to increasing risks across multiple sectors in the US (see Table 1.2 and "Current and Future Climate Risks to the United States" below). Without rapid, substantial reductions in the greenhouse gases that cause global warming, these climate risks in the US are expected to increase.

(**top right**) People born in North America in 2020, on average, will be exposed to more climate-related hazards compared to people born in 1965. How many more extreme climate events current generations experience compared to previous generations will depend on the level of future warming. {Figure 15.4}

(**bottom left**) This climate stripes chart shows the observed changes in US annual average surface temperature for 1951–2022 and projected changes in temperature for 2023–2095 for five climate scenarios, ranging from a very high scenario, where greenhouse gas emissions continue to increase through most of the century, to a very low scenario, where emissions decline rapidly, reaching net zero by around midcentury (see Figure 1.4 and Table 3 in the Guide to the Report). Each vertical stripe represents the observed or projected change in temperature for a given year compared to the 1951–1980 average; changes are averaged over all 50 states and Puerto Rico but do not include data for the US-Affiliated Pacific Islands and the US Virgin Islands (see also Figure 1.13).

(**bottom right**) Although climate benefits from even the most aggressive emissions cuts may not be detectable before the middle of the century, there are many other potential near-term benefits and opportunities from actions that reduce greenhouse gas emissions. {2.3, 8.3, 10.3, 13.3, 14.5, 15.3, 19.1, 31.3, 32.4}

Figure credits: (top left, top center, top right, bottom right) USGCRP, USGCRP/ICF, NOAA NCEI, and CISESS NC; (bottom left) adapted from panel (c) of Figure SPM.1 in IPCC 2023.

Box 1.1. Mitigation, Adaptation, and Resilience

Throughout this report, three important terms are used to describe the primary options for reducing the risks of climate change:

- **Mitigation:** Measures to reduce the amount and rate of future climate change by reducing emissions of heat-trapping gases (primarily carbon dioxide) or removing greenhouse gases from the atmosphere.
- **Adaptation:** The process of adjusting to an actual or expected environmental change and its effects in a way that seeks to moderate harm or exploit beneficial opportunities.
- **Resilience:** The ability to prepare for threats and hazards, adapt to changing conditions, and withstand and recover rapidly from adverse conditions and disruptions.

James Keul

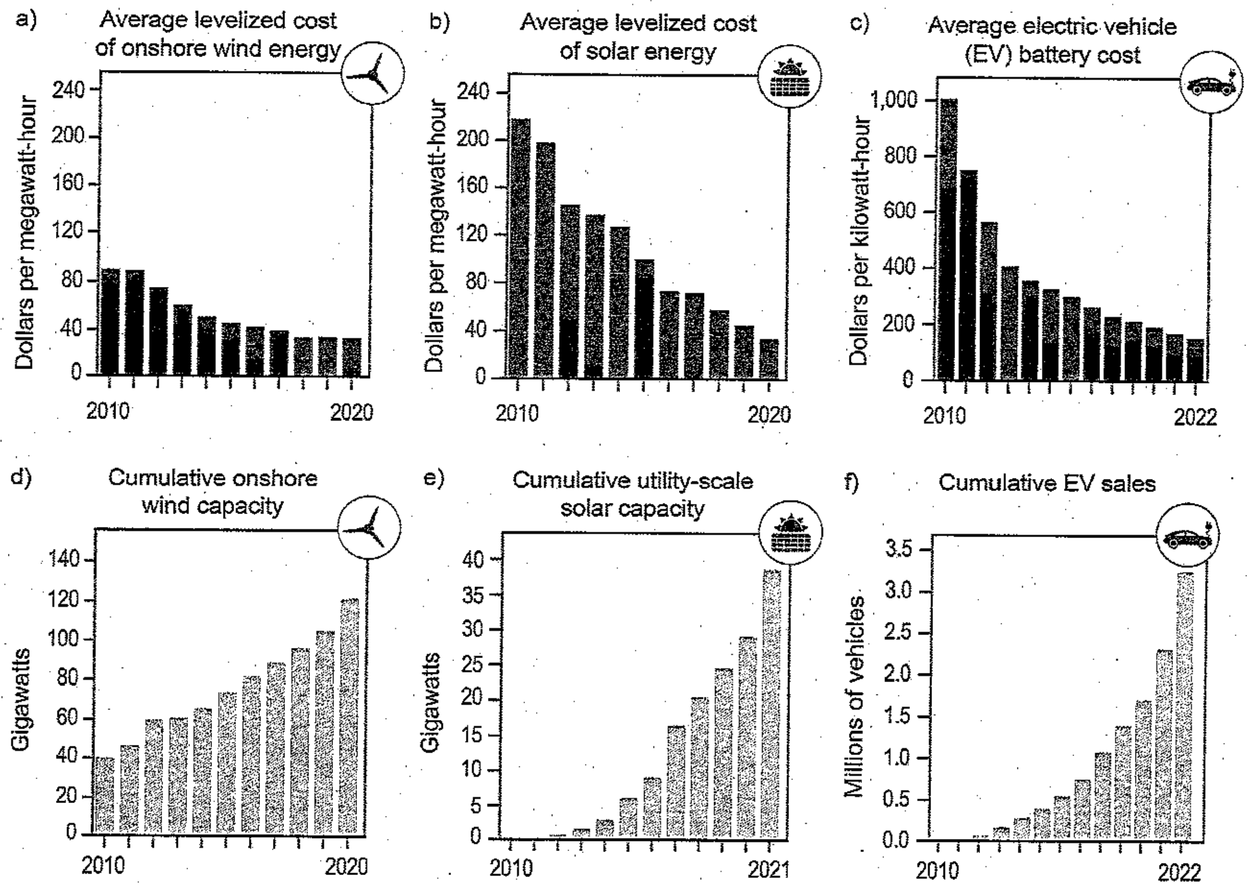
US emissions have decreased, while the economy and population have grown

Annual US greenhouse gas emissions fell 12% between 2005 and 2019. This trend was largely driven by changes in electricity generation: coal use has declined, while the use of natural gas and renewable technologies has increased, leading to a 40% drop in emissions from the electricity sector. Since 2017, the transportation sector has overtaken electricity generation as the largest emitter. {11.1, 13.1, 32.1; Figures 32.1, 32.3}

As US emissions have declined from their peak in 2007, the country has also seen sustained reductions in the amount of energy required for a given quantity of economic activity and the emissions produced per unit of energy consumed. Meanwhile, both population and per capita GDP have continued to grow. {32.1; Figures 32.1, 32.2}

Recent growth in the capacities of wind, solar, and battery storage technologies is supported by rapidly falling costs of zero- and low-carbon energy technologies, which can support even deeper emissions reductions. For example, wind and solar energy costs dropped 70% and 90%, respectively, over the last decade, while 80% of new generation capacity in 2020 came from renewable sources (Figures 1.2, 1.3). {5.3, 12.3, 32.1, 32.2; Figure A4.17}

Across all sectors, innovation is expanding options for reducing energy demand and increasing energy efficiency, moving to zero- and low-carbon electricity and fuels, electrifying energy use in buildings and transportation, and adopting practices that protect and improve natural carbon sinks that remove and store CO_2 from the atmosphere, such as sustainable agricultural and land-management practices. {11.1, 32.2, 32.3; Boxes 32.1, 32.2; Focus on Blue Carbon}



Historical Trends in Unit Costs and Deployment of Low-Carbon Energy Technologies in the United States

Increasing capacities and decreasing costs of low-carbon energy technologies are supporting efforts to further reduce emissions.

Figure 1.2. Costs of onshore wind (a), solar photovoltaics (**b**), and electric vehicle (EV) batteries (**c**) have decreased sharply since 2000 (data shown here start in 2010), as the cumulative capacities of wind and solar generation (**d** and **e**) and the cumulative number of EVs sold (**f**) have increased. {Figure 32.8} Figure credit: Electric Power Research Institute, National Renewable Energy Laboratory, NOAA NCEI, and CISESS NC.

Accelerating advances in adaptation can help reduce rising climate risks

As more people face more severe climate impacts, individuals, organizations, companies, communities, and governments are taking advantage of adaptation opportunities that reduce risks. State climate assessments and online climate services portals are providing communities with location- and sector-specific information on climate hazards to support adaptation planning and implementation across the country. New tools, more data, advancements in social and behavioral sciences, and better consideration of practical experiences are facilitating a range of actions (Figure 1.3). {7.3, 12.3, 21.4, 25.4, 31.1, 31.5, 32.5; Table 31.1}

Actions include:

- Implementing nature-based solutions—such as restoring coastal wetlands or oyster reefs—to reduce shoreline erosion {8.3, 9.3, 21.2, 23.5}
- Upgrading stormwater infrastructure to account for heavier rainfall {4.2}
- Applying innovative agricultural practices to manage increasing drought risk {11.1, 22.4, 25.5}
- Assessing climate risks to roads and public transit {13.1}
- Managing vegetation to reduce wildfire risk {5.3}
- Developing urban heat plans to reduce health risks from extreme heat {12.3, 21.1, 28.4}
- Planning relocation from high-risk coastal areas {9.3}

Despite an increase in adaptation actions across the country, current adaptation efforts and investments are insufficient to reduce today's climate-related risks and keep pace with future changes in the climate. Accelerating current efforts and implementing new ones that involve more fundamental shifts in systems and practices can help address current risks and

Pam DeChellis

prepare for future impacts (see "Mitigation and adaptation actions can result in systemic, cascading benefits" below). {31.1, 31.3}

Climate action has increased in every region of the US

Efforts to adapt to climate change and reduce net greenhouse gas emissions are underway in every US region and have expanded since 2018 (Figure 1.3; Table 1.1). Many actions can achieve both adaptation and mitigation goals. For example, improved forest- or land-management strategies can both increase carbon storage and protect ecosystems, and expanding renewable energy options can reduce emissions while also improving resilience. {31.1, 32.5}

US Adaptation and Mitigation Actions

Cities and states are acting on climate change, with a substantial increase in new activities underway since 2018.

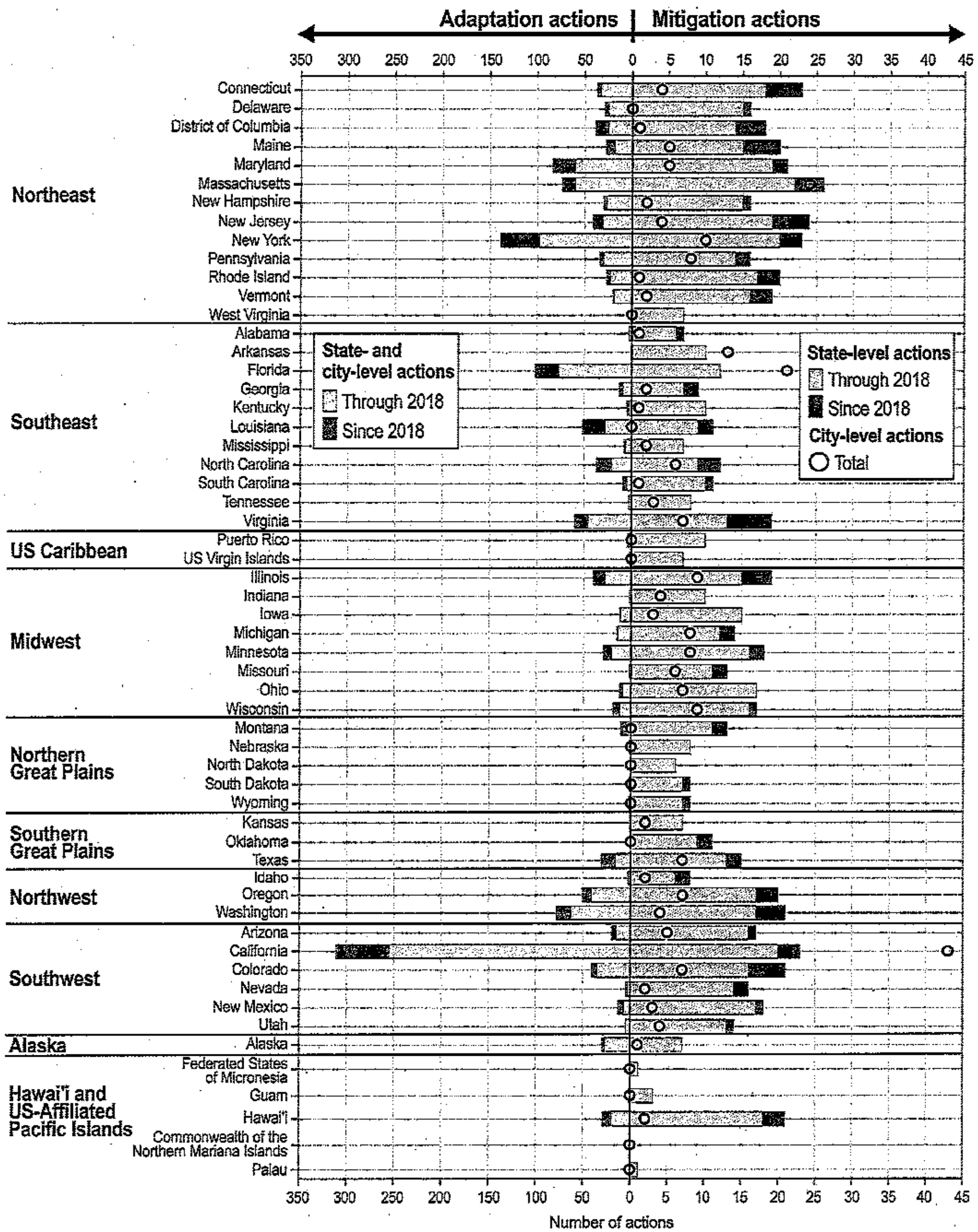


Figure 1.3. Since 2018, city- and state-level adaptation plans and actions (**green bars**, left) increased by 32%, complemented by a 14% increase in the total number of new state-level mitigation activities (**blue bars**, right; 69% have updated their policies). In 2021 there were 271 city-level mitigation actions in place (**open circles**, right), according to the Global Climate Action Tracker. Renewable energy and energy efficiency projects on Tribal lands have also expanded (not shown). {31.1, 32.5; Figure 16.4; Table 1.1} Figure credit: US Army Corps of Engineers, EPA, Pennsylvania State University, NOAA NCEI, and CISESS-NC.

Climate adaptation and mitigation efforts involve trade-offs, as climate actions that benefit some or even most people can result in burdens to others. To date, some communities have prioritized equitable and inclusive planning processes that consider the social impacts of these trade-offs and help ensure that affected communities can participate in decision-making. As additional measures are implemented, more widespread consideration of their social impact can help inform decisions around how to distribute the outcomes of investments. {12.4, 13.4, 20.2, 21.3, 21.4, 26.4, 27.1, 31.2, 32.4, 32.5; Box 20.1}

Table 1.1. Climate Actions Are Taking Place Across All US Regions

Examples of recent local adaptation, resilience, and mitigation actions around the country follow.

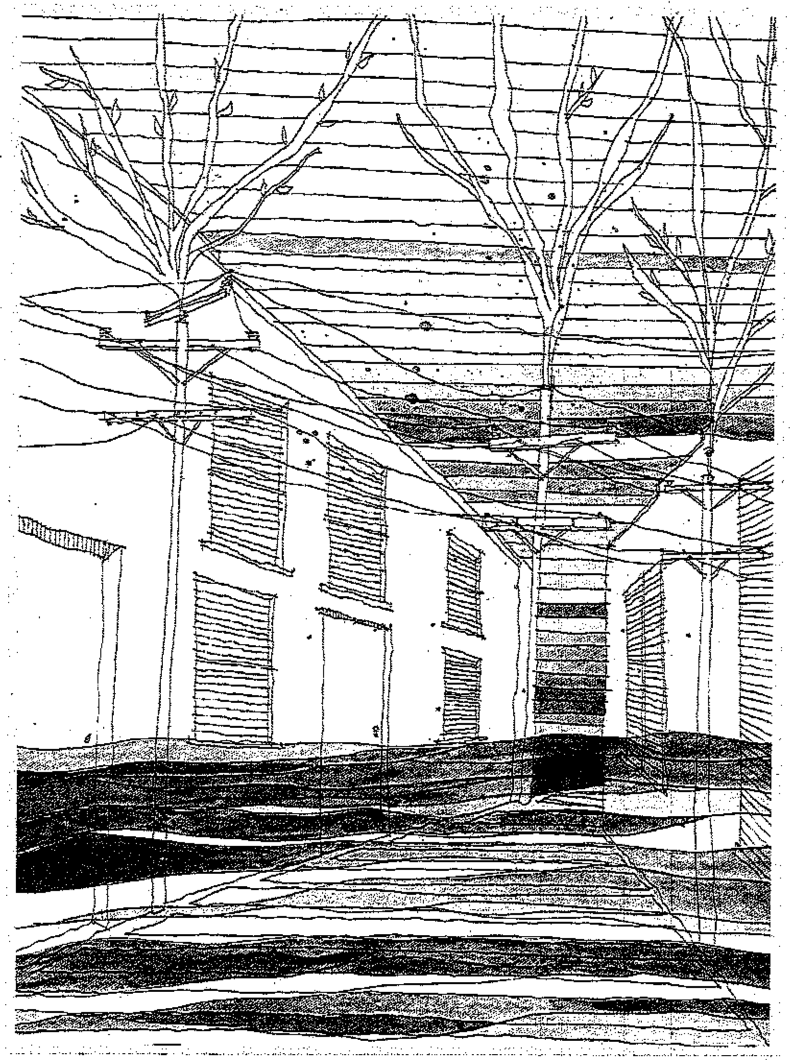
Region	Action
Northeast	The 2022 stormwater code in Pittsburgh, Pennsylvania, requires new developments to plan for projected increases in heavy rainfall under climate change rather than building to historical rainfall amounts. In 2021, the city also committed to achieve carbon neutrality by 2050. {Box 21.1}
Southeast	Following repeated flooding from multiple hurricanes, measures to reduce flood risk in Princeville, North Carolina, include buyouts, elevating homes, and building housing that meets local flood standards. In Orlando, Florida, the city and businesses are adopting commercial building energy-efficiency requirements and electric vehicle readiness policies and have used wastewater and food scraps from parks and resorts to generate renewable biogas. {Boxes 22.1, 32.3}
US Caribbean	Many community-based organizations in Puerto Rico have undertaken actions to advance adaptation, social transformation, and sustainable development. These organizations work to expand renewable energy and equitable access to energy resources, prepare for disasters, restore ecosystems, strengthen agriculture and food security, and protect public health. {23.5}
Midwest	A wetland creation project in Ashtabula, Ohio, restored habitat displaced by shoreline development, improving coastal protection for the port on Lake Erie. In Michigan, some state forestlands are being managed to bolster carbon storage and to support recreation and wildlife habitat. {24.2, 24.4; Figure 24.9}
Northern Great Plains	The Nebraska Natural Resources Conservation Service supported farmers in testing soil health and evaluating soil management practices that promote climate adaptation. Across the region, wind electricity generation tripled between 2011 and 2021, with a growing number of Tribes leading the Nation's renewable energy transition by installing wind, solar, and hydropower. {25.3, 25.5; Box 25.3}
Southern Great Plains	Texas- and Kansas-based groups are supporting soil and land management practices that increase carbon storage while protecting important ecosystems. Wind and solar energy generation and battery storage capacities have also grown, with the region accounting for 42% of national wind-generated electricity in 2022. {26.2}
Northwest	The Confederated Tribes of the Colville Reservation are prioritizing carbon capture in their forest and timber management efforts, leading to improved air and water quality and wildlife habitat as well as preservation of cultural areas and practices. {27.3}
Southwest	In response to severe drought, seven Colorado River basin states, the US and Mexican governments, and Indigenous Peoples are collaborating to improve water conservation and develop adaptation solutions. Dozens of cities are committed to emissions reductions; for instance, Phoenix is on track to meet a 2030 goal of 50% reduction in greenhouse gas emissions from 2018 levels. {Ch. 28, Introduction; Box 28.1}
Alaska	To address climate threats to traditional foods, the Chugach Regional Resources Commission is integrating Indigenous Knowledge and Western scientific methods in its adaptation efforts, including weekly water sampling for harmful algal blooms and restoring clam populations. Kelp farming is also being developed to reduce the effects of ocean acidification, serve as a carbon sink, and generate income. {29.7; Box 29.7}
Hawai'i and US-Affiliated Pacific Islands	The Kaua'i Island Utility Cooperative achieved a 69.5% renewable portfolio standard in 2021, and the island is occasionally 100% renewably powered during midday hours; it is projected to achieve a 90% renewable portfolio by 2026. Guam, the Republic of the Marshall Islands, the Federated States of Micronesia, and Palau plan to use blue carbon ecosystems to offset emissions while also protecting coastal infrastructure. {30.3; Box 30.3}

Meeting US mitigation targets means reaching net-zero emissions

The global warming observed over the industrial era is unequivocally caused by greenhouse gas emissions from human activities—primarily burning fossil fuels. Atmospheric concentrations of carbon dioxide (CO_2)—the primary greenhouse gas produced by human activities—and other greenhouse gases continue to rise due to ongoing global emissions. Stopping global warming would require both reducing emissions of CO_2 to net zero and rapid and deep reductions in other greenhouse gases. Net-zero CO_2 emissions means that CO_2 emissions decline to zero or that any residual emissions are balanced by removal from the atmosphere. {2.3, 3.1; Ch. 32}

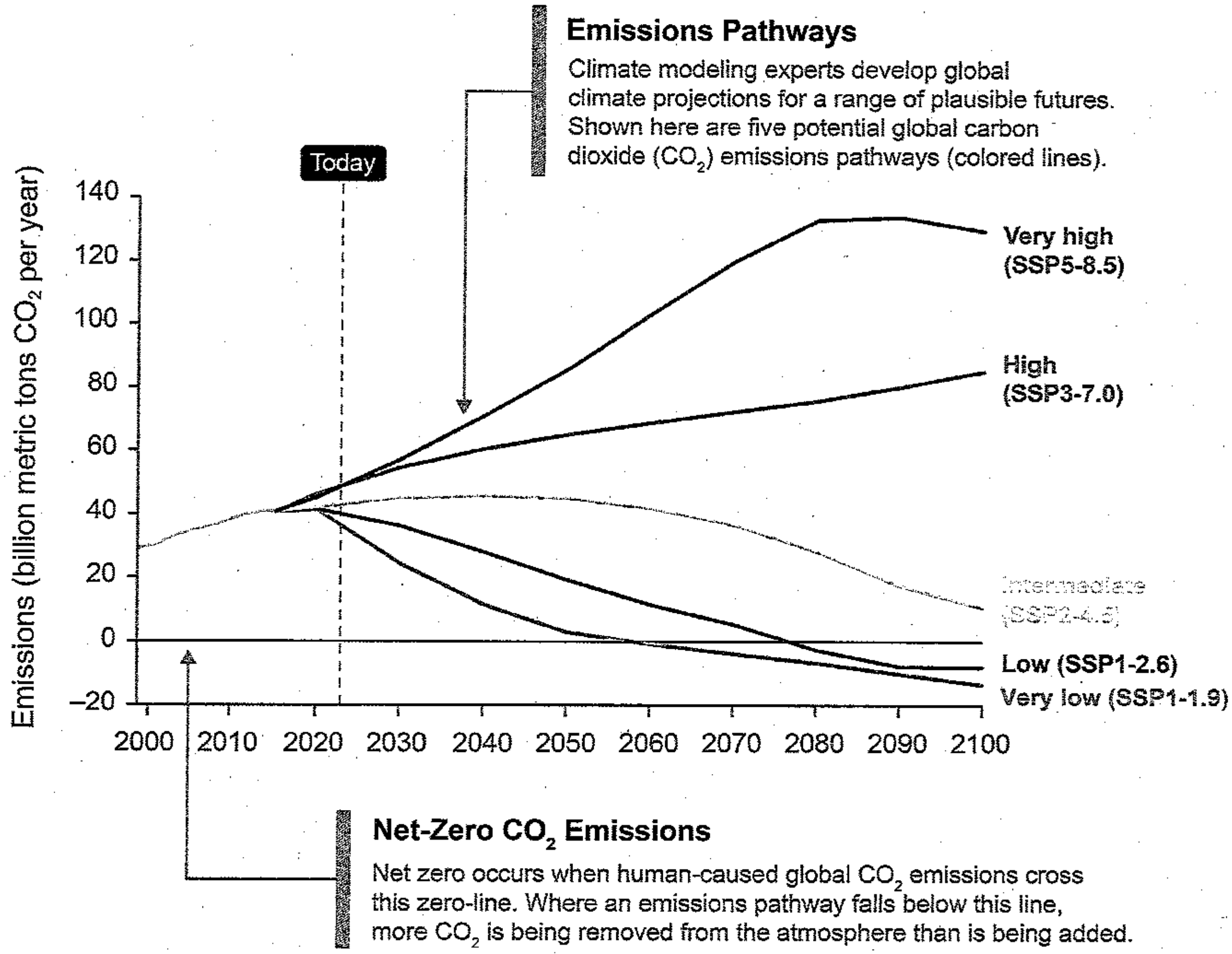
Once CO_2 emissions reach net zero, the global warming driven by CO_2 is expected to stop: additional warming over the next few centuries is not necessarily "locked in" after net CO_2 emissions fall to zero. However, global average temperatures are not expected to fall for centuries unless CO_2 emissions become net negative, which is when CO_2 removal from the atmosphere exceeds CO_2 emissions from human activities. Regardless of when or if further warming is avoided, some long-term responses to the temperature changes that have already occurred will continue. These responses include sea level rise, ice sheet losses, and associated disruptions to human health, social systems, and ecosystems. In addition, the ocean will continue to acidify after the world reaches net-zero CO_2 emissions, as it continues to gradually absorb CO_2 in the atmosphere from past emissions. {2.1, 2.3, 3.1; Ch. 2, Introduction}

National and international commitments seek to limit global warming to well below 2°C (3.6°F), and preferably to 1.5°C (2.7°F), compared to preindustrial temperature conditions (defined as the 1850–1900 average). To achieve this, global CO_2 emissions would have to reach net zero by around 2050 (Figure 1.4); global emissions of all greenhouse gases would then have to reach net zero within the following few decades. {2.3, 32.1}



Andrea Ruedy Trimble

Future Global Carbon Dioxide Emissions Pathways



Different scenarios of future carbon dioxide emissions are used to explore the range of possible climate futures.

Figure 1.4. The five scenarios shown (colored lines) demonstrate potential global carbon dioxide (CO_2) emissions pathways modeled from 2015 through 2100, with the solid light gray line showing observed global CO_2 emissions from 2000 to 2015. See Table 3 in the Guide to the Report for scenario definitions. Many projected impacts described in this report are based on a potential climate future defined by one or more of these scenarios for future CO_2 emissions from human activities, the largest long-term driver of climate change. The vertical dashed line, labeled "Today," marks the year 2023; the solid horizontal black line marks net-zero CO_2 emissions. Adapted with permission from Figure TS.4 in Arias et al. 2021.

While US greenhouse gas emissions are falling, the current rate of decline is not sufficient to meet national and international climate commitments and goals. US net greenhouse gas emissions remain substantial and would have to decline by more than 6% per year on average, reaching net-zero emissions around midcentury, to meet current national mitigation targets and international temperature goals; by comparison, US greenhouse gas emissions decreased by less than 1% per year on average between 2005 and 2019. {32.1}

Many cost-effective options that are feasible now have the potential to substantially reduce emissions over the next decade. Faster and more widespread deployment of renewable energy and other zero- and low-carbon energy options can accelerate the transition to a decarbonized economy and increase the chances of meeting a 2050 national net-zero greenhouse gas emissions target for the US. However, to reach the US net-zero emissions target, additional mitigation options need to be explored and advanced (see "Available mitigation strategies can deliver substantial emissions reductions, but additional options are needed to reach net zero" below). {5.3, 6.3, 32.2, 32.3}

David Zeiset

How the United States Is Experiencing Climate Change

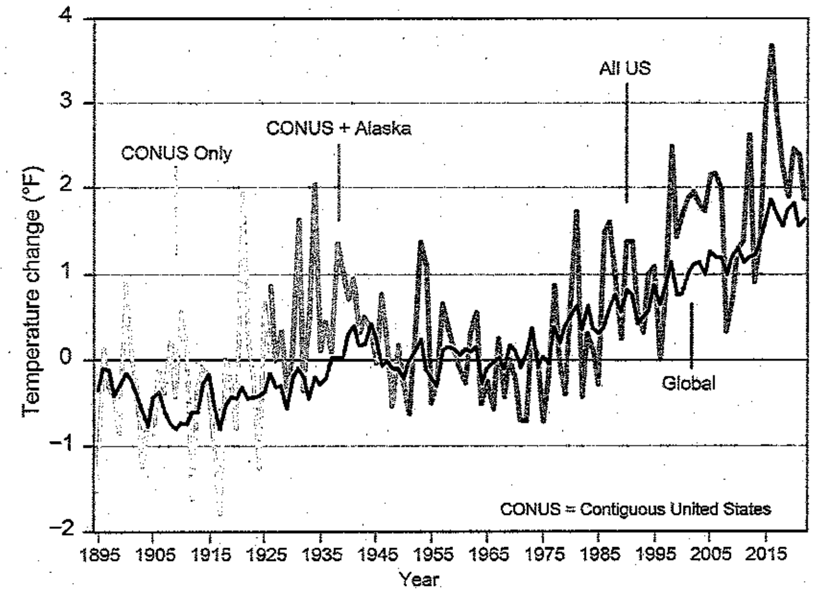
As extreme events and other climate hazards intensify, harmful impacts on people across the United States are increasing. Climate impacts—combined with other stressors—are leading to ripple effects across sectors and regions that multiply harms, with disproportionate effects on underserved and overburdened communities.

Current climate changes are unprecedented over thousands of years

Global greenhouse gas emissions from human activities continue to increase, resulting in rapid warming (Figure 1.5) and other large-scale changes, including rising sea levels, melting ice, ocean warming and acidification, changing rainfall patterns, and shifts in timing of seasonal events. Many of the climate conditions and impacts people are experiencing today are unprecedented for thousands of years (Figure 1.6). {2.1, 3.1; Figures A4.6, A4.7, A4.10, A4.13}

As the world's climate has shifted toward warmer conditions, the frequency and intensity of extreme cold events have declined over much of the US, while the frequency, intensity, and duration of extreme heat have increased. Across all regions of the US, people are experiencing warming temperatures and longer-lasting heatwaves. Over much of the country, nighttime temperatures and winter temperatures have warmed more rapidly than daytime and summer temperatures. Many other extremes, including heavy precipitation, drought, flooding, wildfire, and hurricanes, are becoming more frequent and/or severe, with a cascade of effects in every part of the country. {2.1, 2.2, 3.4, 4.1, 4.2, 7.1, 9.1; Ch. 2, Introduction; App. 4; Focus on Compound Events}

US and Global Changes in Average Surface Temperature



The US has warmed rapidly since the 1970s.

Figure 1.5. The graph shows the change in US annual average surface temperature during 1895–2022 compared to the 1951–1980 average. The temperature trend changes color as data become available for more regions of the US, with Alaska data added to the average temperature for the contiguous US (CONUS) beginning in 1926 (medium blue line) and Hawai'i, Puerto Rico, and US-Affiliated Pacific Islands data added beginning in 1951 (dark blue line). Global average surface temperature is shown by the black line. Figure credit: NOAA NCEI and CISESS NC.

Rapid and Unprecedented Changes

800k years — Present-day levels of greenhouse gases in the atmosphere are higher than at any time in at least the past 800,000 years, with most of these emissions occurring since 1970.

3,000 years — The rate of sea level rise in the 20th century was faster than in any other century in at least the last 3,000 years.

2,000 years — Global temperature has increased faster in the past 50 years than at any time in at least the past 2,000 years.

1,200 years — The current drought in the western US is now the most severe drought in at least 1,200 years and has persisted for decades.

Current climate conditions are unprecedented for thousands of years.

Figure 1.6. Human activities since industrialization have led to increases in atmospheric greenhouse gas concentrations that are unprecedented in records spanning hundreds of thousands of years. These are examples of some of the large and rapid changes in the climate system that are occurring as the planet warms. (Greenhouse gas concentrations {2.1}; sea level rise {3.4}; global temperature {2.1}; drought {2.2, 3.5}) Figure credit: USGCRP and ICF.

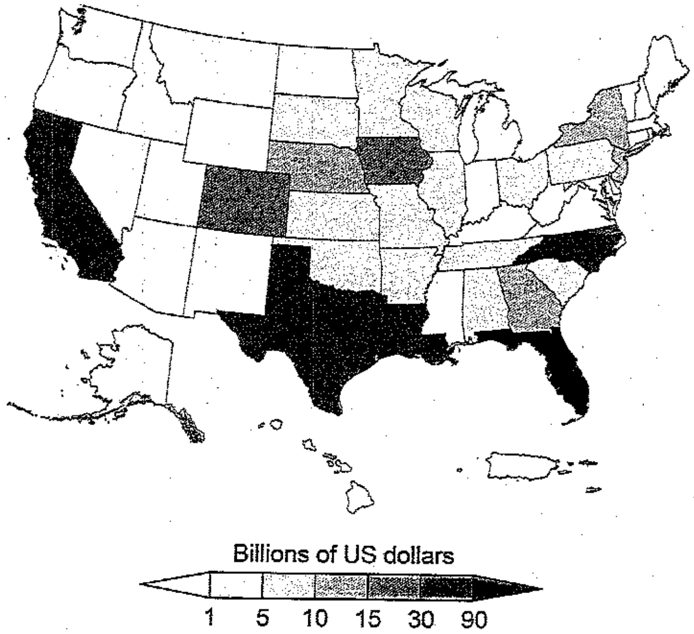
Risks from extreme events are increasing

One of the most direct ways that people experience climate change is through changes in extreme events. Harmful impacts from more frequent and severe extremes are increasing across the country—including increases in heat-related illnesses and death, costlier storm damages, longer droughts that reduce agricultural productivity and strain water systems, and larger, more severe wildfires that threaten homes and degrade air quality. {2.2, 4.2, 12.2, 14.2, 15.1, 19.2; Focus on Western Wildfires}

Extreme weather events cause direct economic losses through infrastructure damage, disruptions in labor and public services, and losses in property values. The number and cost of weather-related disasters have increased dramatically over the past four decades, in part due to the increasing frequency and intensity of extreme events and in part due to increases in assets at risk (through population growth, rising property values, and continued development in hazard-prone areas). Low-income communities, communities of color, and Tribes and Indigenous Peoples experience high exposure and vulnerability to extreme events due to both their proximity to hazard-prone areas and lack of adequate infrastructure or disaster management resources. {2.2, 4.2, 17.3, 19.1; Focus on Compound Events}

In the 1980s, the country experienced, on average, one (inflation-adjusted) billion-dollar disaster every four months. Now, there is one every three weeks, on average. Between 2018 and 2022, the US experienced 89 billion-dollar events (Figure 1.7). Extreme events cost the US close to $150 billion each year—a conservative estimate that does not account for loss of life, healthcare-related costs, or damages to ecosystem services. {2.2, 19.1; Ch. 2, Introduction; Figures 4.1, A4.5}

Damages by State from Billion-Dollar Disasters (2018–2022)



The US now experiences, on average, a billion-dollar weather or climate disaster every three weeks.

Figure 1.7. Billion-dollar weather and climate disasters are events where damages/costs reach or exceed $1 billion, including adjustments for inflation. Between 2018 and 2022, 89 such events affected the US, including 4 droughts, 6 floods, 52 severe storms, 18 tropical cyclones, 5 wildfires, and 4 winter storm events (see Figure A4.5 for the number of billion-dollar disasters per year). During this period, Texas had the highest total damages ($375 billion); Florida experienced the highest damages from a single event—Hurricane Ian ($113 billion). While similar data are not available for the US-Affiliated Pacific Islands, Super Typhoon Yutu caused $500 million in property damage alone in Saipan and the northern Marianas in 2018 (NCEI 2019). Increasing costs over time are driven by changes in the assets at risk and the increase in frequency or intensity of extreme events caused by climate change. Adapted from NCEI 2023.

Cascading and compounding impacts increase risks

The impacts and risks of climate change unfold across interacting sectors and regions. For example, wildfire in one region can affect air quality and human health in other regions, depending on where winds transport smoke. Further, climate change impacts interact with other stressors, such as the COVID-19 pandemic, environmental degradation, or socioeconomic stressors like poverty and lack of adequate housing that disproportionately impact overburdened communities. These interactions and interdependencies can lead to cascading impacts and sudden failures. For example, climate-related shocks to the food supply chain have led to local to global impacts on food security and human migration patterns that affect US economic and national security interests. {11.3, 17.1, 17.2, 17.3, 18.1, 22.3, 23.4, 31.3; Introductions in Chs. 2, 17, 18; Focus on Compound Events; Focus on Risks to Supply Chains; Focus on COVID-19 and Climate Change}

The risk of two or more extreme events occurring simultaneously or in quick succession in the same region—known as compound events—is increasing. Climate change is also increasing the risk of multiple extremes occurring simultaneously in different locations that are connected by complex human and natural systems. For instance, simultaneous megafires across multiple western states and record back-to-back Atlantic hurricanes in 2020 caused unprecedented demand on federal emergency response resources. {2.2, 3.2, 15.1, 22.2, 26.4; Focus on Compound Events; Ch. 4, Introduction}

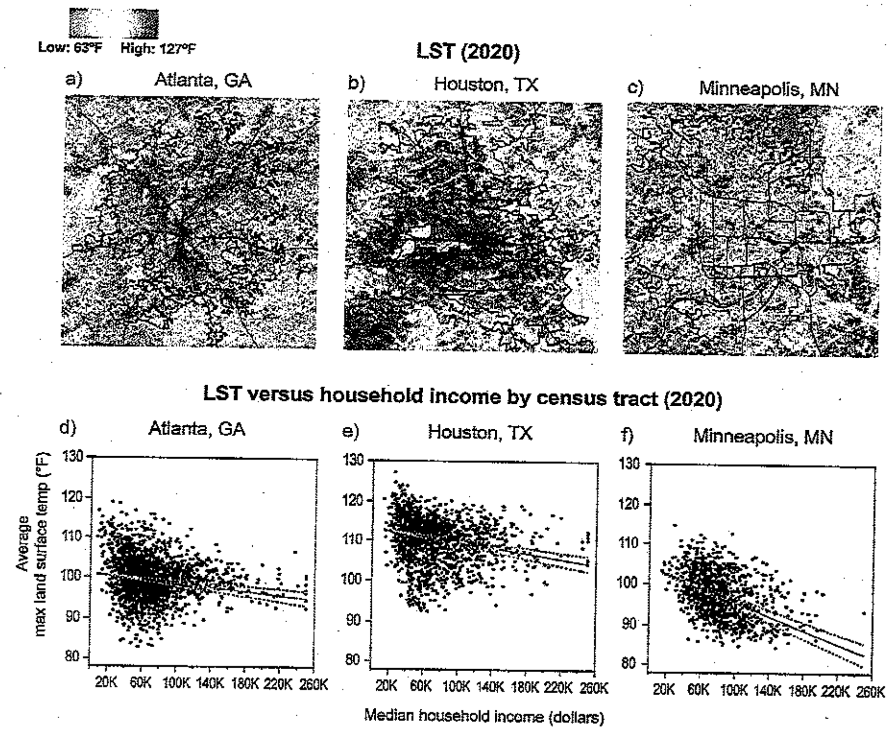
Compound events often have cascading impacts that cause greater harm than individual events. For example, in 2020, record-breaking heat and widespread drought contributed to concurrent destructive wildfires across California, Oregon, and Washington, exposing millions to health hazards and straining firefighting resources. Ongoing drought amplified the record-breaking Pacific Northwest heatwave of June 2021, which was made 2° to 4°F hotter by climate change. The heatwave led to more than 1,400 heat-related deaths, another severe wildfire season, mass die-offs of fishery species important to the region's economy and Indigenous communities, and total damages exceeding $38.5 billion (in 2022 dollars). {27.3; Ch. 2, Introduction; Focus on Compound Events, Focus on Western Wildfires}

Climate change exacerbates inequities

Some communities are at higher risk of negative impacts from climate change due to social and economic inequities caused by ongoing systemic discrimination, exclusion, and under- or disinvestment. Many such communities are also already overburdened by the cumulative effects of adverse environmental, health, economic, or social conditions. Climate change worsens these long-standing inequities, contributing to persistent disparities in the resources needed to prepare for, respond to, and recover from climate impacts. {4.2, 9.2, 12.2, 14.3, 15.2, 16.1, 16.2, 18.2, 19.1, 20.1, 20.3, 21.3, 22.1, 23.1, 26.4, 27.1, 31.2}

For example, low-income communities and communities of color often lack access to adequate flood infrastructure, green spaces, safe housing, and other resources that help protect people from climate impacts. In some areas, patterns of urban growth have led to the displacement of under-resourced communities to suburban and rural areas with less access to climate-ready housing and infrastructure. Extreme heat can lead to higher rates of illness and death in low-income neighborhoods, which are hotter on average (Figure 1.8). Neighborhoods that are home to racial minorities and low-income people have the highest inland (riverine) flood exposures in the South, and Black communities nationwide are expected to bear a disproportionate share of future flood damages—both coastal and inland (Figure 1.9). {4.2, 11.3, 12.2, 15.1, 22.1, 22.2, 26.4, 27.1; Ch. 2, Introduction}

Land Surface Temperature and Its Relationship to Median Household Income for Three Cities

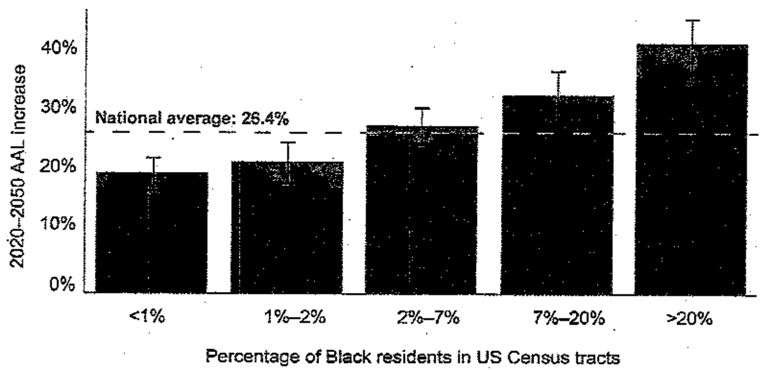


Lower-income urban neighborhoods experience higher surface temperatures.

Figure 1.8. The figure shows the spatial distribution of maximum land surface temperature (LST) in 2020 for Atlanta (**a**), Houston (**b**), and Minneapolis (**c**). Graphs (**d**), (**e**), and (**f**) depict the relationship between maximum LST and median household income across census tracts in each city (see also Figure A4.4). A statistical trend analysis (the Theil-Sen estimator) returns negative values for all three cities, indicating that LST decreases as income increases (solid red line). Dashed red lines indicate the 95% confidence interval, meaning that the true slope of the trend is expected to fall within this range. Note that LST is measured at ground level and may differ from surface air temperature, which is measured at a height of 2 meters. {Figure 12.6} Portions of this figure include intellectual property of Esri and its licensors and are used under license.
Figure credit: University of California, Davis; University of Texas at El Paso; Massachusetts Institute of Technology; City of Phoenix, Arizona; and USGS.

These disproportionate impacts are partly due to exclusionary housing practices—both past and ongoing—that leave underserved communities with less access to heat and flood risk-reduction strategies and other economic, health, and social resources. For example, areas that were historically redlined—a practice in which lenders avoided providing services to communities, often based on their racial or ethnic makeup—continue to be deprived of equitable access to environmental amenities like urban green spaces that reduce exposure to climate impacts. These neighborhoods can be as much as 12°F hotter during a heatwave than nearby wealthier neighborhoods. {8.3, 9.2, 12.2, 15.2, 20.3, 21.3, 22.1, 26.4, 27.1, 32.4; Ch. 2, Introduction}

Projected Increases in Average Annual Losses (AALs) from Floods by 2050



Losses due to floods are projected to increase disproportionately in US Census tracts with higher percentages of Black residents.

Figure 1.9. The bars show that the average annual losses—or the economic damage in a typical year—due to floods in census tracts with a Black population of at least 20% are projected to increase at roughly twice the rate of that in tracts where Black populations make up less than 1% of population. {Figure 4.14} Adapted from Wing et al. 2022 [CC BY 4.0].

Harmful impacts will increase in the near term

Even if greenhouse gas emissions fall substantially, the impacts of climate change will continue to intensify over the next decade (see "Meeting US mitigation targets means reaching net-zero emissions" above; Box 1.4), and all US regions are already experiencing increasingly harmful impacts. Although a few US regions or sectors may experience limited or short-term benefits from climate change, adverse impacts already far outweigh any positive effects and will increasingly eclipse benefits with additional warming. {2.3, 19.1; Ch. 2, Introduction; Chs. 21–30}

Table 1.2 shows examples of critical impacts expected to affect people in each region between now and 2030, with disproportionate effects on overburdened communities. While these examples affect particular regions in the near term, impacts often cascade through social and ecological systems and across borders and may lead to longer-term losses. {15.2, 18.2, 20.1; Figure 15.5; Ch. 20, Introduction}

Table 1.2. Climate Change Is Already Affecting All US Regions and Will Continue to Have Impacts in the Near Term

The table shows three climate impacts of significant concern to each US region between now and 2030. Icons indicate general categories of impacts: infrastructure, water supply, health and well-being, food security, economy, livelihoods and heritage, and ecosystems. More information can be found in the regional chapters (Chs. 21–30).

Infrastructure · Water Supply · Health and Well-Being · Food Security · Economy · Livelihoods and Heritage · Ecosystems

Northeast

- Extreme weather events damage critical infrastructure. {21.1}
- Warming temperatures shift distributions of coastal and marine species and habitats. {21.2}
- Extreme heat and flooding disproportionately impact overburdened communities. {21.3}

US Caribbean

- Agricultural losses, especially from tropical cyclones, threaten food security. {23.1}
- Severe drought leads to large agricultural and economic losses. {23.3}
- Rising temperatures increase mortality and power demand; hurricanes and storms stress power grids. {23.2, 23.4}

Northern Great Plains

- Rising temperatures and decreasing snowpack reduce water supply. {25.1}
- Increases in extreme heat, wildfire, and flooding harm physical and mental health. {25.1, 25.2}
- Livelihoods are at greater risk, especially in agriculture, recreation, and energy sectors. {25.3}

Southeast

- Sea level rise and coastal flooding harm rapidly growing communities. {22.1}
- Extreme heat threatens human health, especially stressing urban communities. {22.2}
- Heavy rain and longer dry spells reduce water supply and access. {22.4}

Midwest

- Rising temperatures and extreme events threaten livelihoods and trades. {24.2}
- Extreme weather events harm public health. {24.3}
- Rising temperatures and extreme rainfall damage buildings, homes, and businesses. {24.4}

Southern Great Plains

- Drier conditions threaten agriculture, ecosystems, and water supplies. {26.1, 26.2, 26.5}
- Extreme heat and high humidity harm human health and exacerbate inequities. {26.4}
- Multiple stressors and extreme events disrupt business, outdoor recreation, and leisure activities. {26.1, 26.2, 26.3}

Northwest

- Less water is available for hydropower, rural communities, and aquatic ecosystems. {27.1, 27.2, 27.4}
- Extreme heat and wildfire smoke endanger at-risk urban, rural, and Tribal communities. {27.1, 27.3, 27.5}
- Wildfire, extreme heat, and floods threaten livelihoods and heritage tied to natural resources. {27.1, 27.3, 27.6}

Alaska

- Landscape degradation increases damage to private and municipal infrastructure. {29.2, 29.4}
- Reduced fish stocks harm local economies, Tribal sovereignty, and overall well-being. {29.6, 29.7}
- Diminished access to mammals, seabirds, fish, and vegetation decreases local food security. {29.5}

Southwest

- Intensifying drought and decreases in groundwater recharge reduce water supply. {28.1}
- Economic losses to farmers and ranchers increase. {28.3}
- Extreme heat, drought, wildfire smoke, and coastal flooding harm physical and mental health. {28.3, 28.4}

Hawai'i and US-Affiliated Pacific Islands

- Sea level rise and saltwater intrusion reduce irrigation and drinking water supply. {30.1}
- Damages to the coastal built environment, including traditional structures, increase. {30.3, 30.5}
- Risks to unique and biodiverse flora and fauna continue to grow. {30.4}

Current and Future Climate Risks to the United States

Climate changes are making it harder to maintain safe homes and healthy families; reliable public services; a sustainable economy; thriving ecosystems, cultures, and traditions; and strong communities. Many of the extreme events and harmful impacts that people are already experiencing will worsen as warming increases and new risks emerge.

Safe, reliable water supplies are threatened by flooding, drought, and sea level rise

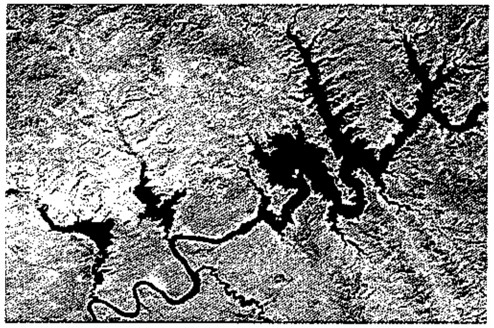
More frequent and intense heavy precipitation events are already evident, particularly in the Northeast and Midwest. Urban and agricultural environments are especially vulnerable to runoff and flooding. Between 1981 and 2016, US corn yield losses from flooding were comparable to those from extreme drought. Runoff and flooding also transport debris and contaminants that cause harmful algal blooms and pollute drinking water supplies. Communities of color and low-income communities face disproportionate flood risks. {2.2, 4.2, 6.1, 9.2, 21.3, 24.1, 24.5, 26.4; Figure A4.8}

Between 1980 and 2022, drought and related heatwaves caused approximately $328 billion in damages (in 2022 dollars). Recent droughts have strained surface water and groundwater supplies, reduced agricultural productivity, and lowered water levels in major reservoirs, threatening hydropower generation. As higher temperatures increase irrigation demand, increased pumping could endanger groundwater supplies, which are already declining in many major aquifers. {4.1, 4.2; Figure A4.9}

Droughts are projected to increase in intensity, duration, and frequency, especially in the Southwest, with implications for surface water and groundwater supplies. Human and natural systems are threatened by rapid shifts between wet and dry periods that make water resources difficult to predict and manage. {2.2, 2.3, 4.1, 4.2, 5.1, 28.1}

In coastal environments, dry conditions, sea level rise, and saltwater intrusion endanger groundwater aquifers and stress aquatic ecosystems. Inland, decreasing snowpack alters the volume and timing of streamflow and increases wildfire risk. Small rural water providers that often depend on a single water source or have limited capacity are especially vulnerable. {4.2, 7.2, 9.2, 21.2, 22.1, 23.1, 23.3, 25.1, 27.4, 28.1, 28.2, 28.5, 30.1; Figure A4.7}

Many options are available to protect water supplies, including reservoir optimization, nature-based solutions, and municipal management systems to conserve and reuse water. Collaboration on flood hazard management at regional scales is particularly important in areas where flood risk is increasing, as cooperation can provide solutions unavailable at local scales. {4.3, 9.3, 26.5; Focus on Blue Carbon}


(**left**; Toledo, Ohio) Rising temperatures are intensifying harmful algal blooms, negatively affecting human and animal health. (**top right**; Utah, Arizona) Water levels on Lake Powell have fallen to historic lows in recent years, affecting millions of people across the Southwest. (**bottom right**) Rain gardens, a form of green infrastructure, absorb excess stormwater. Photo credits: (left) Aerial Associates Photography Inc. by Zachary Haslick; (top right) NASA Earth Observatory images by Lauren Dauphin, using Landsat data from the USGS; (bottom right) Alisha Goldstein, EPA.

Disruptions to food systems are expected to increase

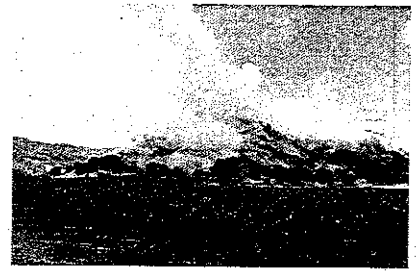
As the climate changes, increased instabilities in US and global food production and distribution systems are projected to make food less available and more expensive. These price increases and disruptions are expected to disproportionately affect the nutrition and health of women, children, older adults, and low-wealth communities. {11.2, 15.2}

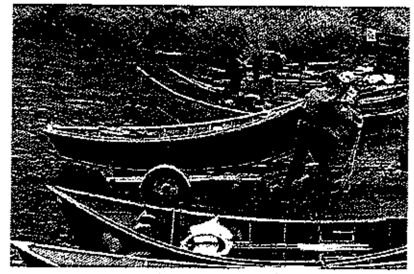
Climate change also disproportionately harms the livelihoods and health of communities that depend on agriculture, fishing, and subsistence lifestyles, including Indigenous Peoples reliant on traditional food sources. Heat-related stress and death are significantly greater for farmworkers than for all US civilian workers. {11.2, 11.3, 15.1, 15.2, 16.1; Focus on Risks to Supply Chains}

While farmers, ranchers, and fishers have always faced unpredictable weather, climate change heightens risks in many ways:

- Increasing temperatures, along with changes in precipitation, reduce productivity, yield, and nutritional content of many crops. These changes can introduce disease, disrupt pollination, and result in crop failure, outweighing potential benefits of longer growing seasons and increased CO_2 fertilization. {11.1, 19.1, 21.1, 22.4, 23.3, 24.1, 26.2}
- Heavy rain and more frequent storms damage crops and property and contaminate water supplies. Longer-lasting droughts and larger wildfires reduce forage production and nutritional quality, diminish water supplies, and increase heat stress on livestock. {23.2, 25.3, 28.3}
- Increasing water temperatures, invasive aquatic species, harmful algal blooms, and ocean acidification and deoxygenation put fisheries at risk. Fishery collapses can result in large economic losses, as well as loss of cultural identity and ways of life. {11.3, 29.3}

In response, some farmers and ranchers are adopting innovations—such as agroecological practices, data-driven precision agriculture, and carbon monitoring—to improve resilience, enhance soil carbon storage, and reduce emissions. Across the Nation, Indigenous food security efforts are helping improve community resilience to climate change while also improving cultural resilience. Some types of aquaculture have the potential to increase climate-smart protein production, human nutrition, and food security, although some communities have raised concerns over issues such as conflict with traditional livelihoods and the introduction of disease or pollution. {10.2, 11.1, 29.6, 25.5; Boxes 22.3, 27.2}





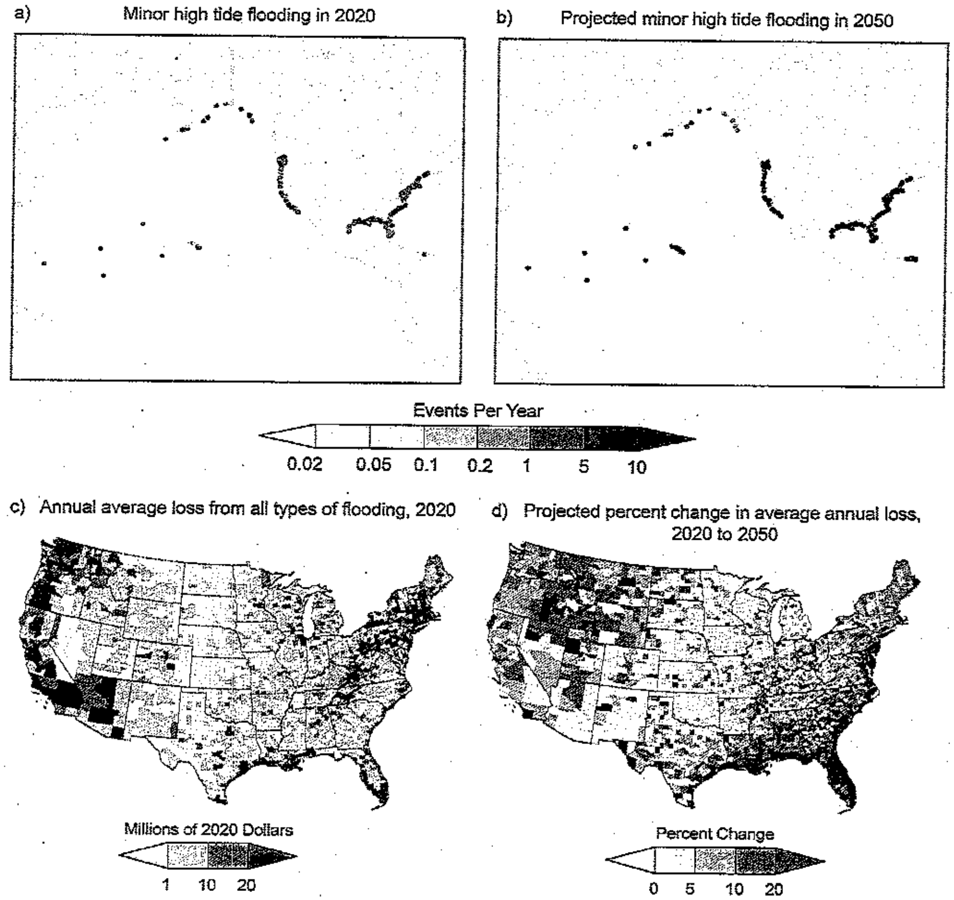
(**left**; Baltimore, Maryland) Urban farms offer the potential to reduce carbon emissions while helping to improve community food security. (**top right**; California) A Northern California vineyard is affected by wildfire. (**bottom right**; Kenai River, Alaska) Recent climate extremes have contributed to declines in many salmon populations. Photo credits: (left) Preston Keres, USDA/FPAC; (top right) Ordinary Mario/iStock via Getty Images; (bottom right) Eric Vance, EPA.

Homes and property are at risk from sea level rise and more intense extreme events

Homes, property, and critical infrastructure are increasingly exposed to more frequent and intense extreme events, increasing the cost of maintaining a safe and healthy place to live. Development in fire-prone areas and increases in area burned by wildfires have heightened risks of loss of life and property damage in many areas across the US. Coastal communities across the country—home to 123 million people (40% of the total US population)—are exposed to sea level rise (Figure 1.10), with millions of people at risk of being displaced from their homes by the end of the century. {2.3, 9.1, 12.2, 22.1, 27.4, 30.3; Figures A4.10, A4.14; Focus on Western Wildfires}

People who regularly struggle to afford energy bills—such as rural, low-income, and older fixed-income households and communities of color—are especially vulnerable to more intense extreme heat events and associated health risks, particularly if they live in homes with poor insulation and inefficient cooling systems. For example, Black Americans are more likely to live in older, less energy efficient homes and face disproportionate heat-related health risks. {5.2, 15.2, 15.3, 22.2, 26.4, 32.4; Figure A4.4}

Accessible public cooling centers can help protect people who lack adequate air-conditioning on hot days. Strategic land-use planning in cities, urban greenery, climate-smart building codes, and early warning communication can also help neighborhoods adapt. However, other options at the household scale, such as hardening homes against weather extremes or relocation, may be out of reach for renters and low-income households without assistance. {12.3, 15.3, 19.3, 22.2}



US Flooding Risks in 2020 and 2050

Increasing flooding puts more people and assets at risk.

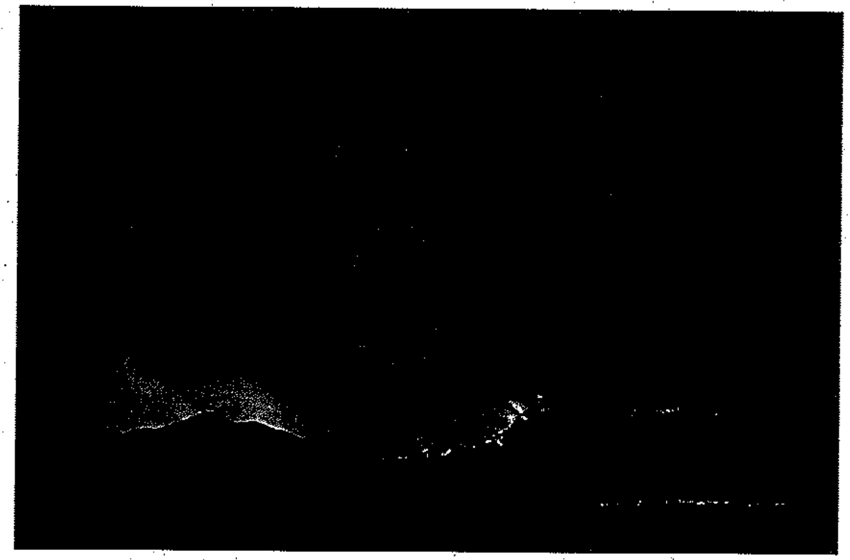
Figure 1.10. (**top row**) Maps show (**a**) the average number of minor high tide flooding events per year in 2020 (with historical sea level rise) and (**b**) the expected number of events per year in 2050 (when driven by extrapolated sea level rise). (**bottom row**) Maps show (**c**) average annual loss (AAL) from all types of flooding in millions of dollars in 2020 and (**d**) the projected changes in AAL in 2050 relative to 2020. AAL estimates were made only for the contiguous US. Over the next three decades, the number of flooding days along all coastlines of the US is expected to increase. These increases in the occurrence of flooding will drive greater AALs, especially in coastal areas of the US. (a, b) Adapted from Sweet et al. 2022; (c, d) adapted from Wing et al. 2022 [CC BY 4.0].

Box 1.2. Migration and Displacement

Extreme events, such as extended drought, wildfire, and major hurricanes, have contributed to human migration and displacement. For example, numerous extreme events over the last two decades drove migration of vulnerable communities in Puerto Rico and the US Virgin Islands to the mainland. {9.2, 15.1, 17.2, 19.2, 23.1, 23.5; Box 18.2}

In the future, the combination of climate change and other factors, such as housing affordability, is expected to increasingly affect migration patterns. More severe wildfires in California, increasing sea level rise in Florida, and more frequent flooding in Texas are expected to displace millions of people. Climate-driven economic changes abroad, including reductions in crop yields, are expected to increase the rate of emigration to the United States. {9.2, 17.2, 19.2, 30.3}

From Alaska to low-lying Pacific atolls, forced migrations and displacements driven by climate change disrupt social networks, decrease housing security, and exacerbate grief, anxiety, and negative mental health outcomes. Indigenous Peoples, who have long faced land dispossession due to settler colonialism, are again being confronted with displacement and loss of traditional resources and practices. {4.2, 15.1, 16.1, 19.1, 20.1, 20.3, 22.1, 22.2, 29.1, 30.3; Box 18.2}



(**left**; Cedar Rapids, Iowa) More frequent and intense heavy precipitation events are already evident, particularly in the Northeast and Midwest. (**right**; Arizona) The 2021 Telegraph Fire destroyed homes and property. Photo credits: (left) Don Becker, USGS; (right) Andrew Avitt, USDA Forest Service.

Infrastructure and services are increasingly damaged and disrupted by extreme weather and sea level rise

Climate change threatens vital infrastructure that moves people and goods, powers homes and businesses, and delivers public services. Many infrastructure systems across the country are at the end of their intended useful life and are not designed to cope with additional stress from climate change. For example, extreme heat causes railways to buckle, severe storms overload drainage systems, and wildfires result in roadway obstruction and debris flows. Risks to energy, water, healthcare, transportation, telecommunications, and waste management systems will continue to rise with further climate change, with many infrastructure systems at risk of failing. {12.2, 13.1, 15.2, 23.4, 26.5; Focus on Risks to Supply Chains}

In coastal areas, sea level rise threatens permanent inundation of infrastructure, including roadways, railways, ports, tunnels, and bridges; water treatment facilities and power plants; and hospitals, schools, and military bases. More intense storms also disrupt critical services like access to medical care, as seen after Hurricanes Irma and Maria in the US Virgin Islands and Puerto Rico. {9.2, 23.1, 28.2, 30.3}

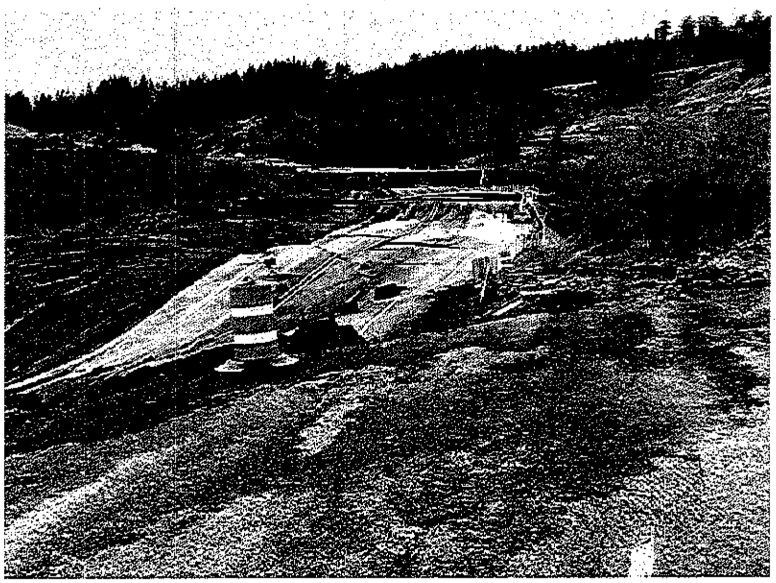
At the same time, climate change is expected to place multiple demands on infrastructure and public services. For example, higher temperatures and other effects of climate change, such as greater exposure to stormwater or wastewater, will increase demand for healthcare. Continued increases in average temperatures and more intense heatwaves will heighten electricity and water demand, while wetter storms and intensified hurricanes will strain wastewater and stormwater management systems. In the Midwest and other regions, aging energy grids are expected to be strained by disruptions and transmission efficiency losses from climate change. {23.4, 24.4, 30.2}

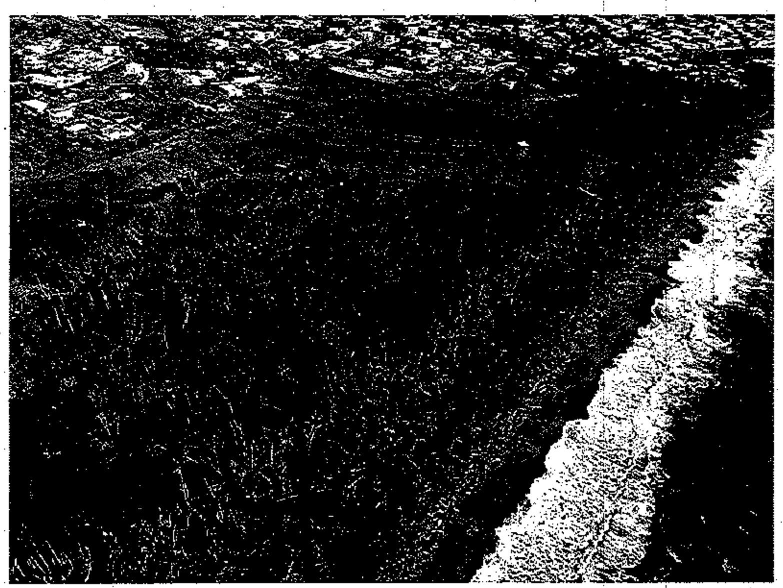
Forward-looking designs of infrastructure and services can help build resilience to climatechange, offset costs from future damage to transportation and electrical systems, and provide other benefits, including meeting evolving standards to protect public health, safety, and welfare. Mitigation and adaptation activities are advancing from planning stages to deployment in many areas, including improved grid design and workforce training for electrification, building upgrades, and land-use choices. Grid managers are gaining experience planning and operating electricity systems with growing shares of renewable generation and working toward understanding the best approaches for dealing with the natural variability of wind and solar sources alongside increases in electrification. {5.3, 12.3, 13.1, 13.2, 22.3, 24.4, 32.3; Figure 22.17}

Climate change exacerbates existing health challenges and creates new ones

Climate change is already harming human health across the US, and impacts are expected to worsen with continued warming. Climate change harms individuals and communities by exposing them to a range of compounding health hazards, including the following:

- More severe and frequent extreme events {2.2, 2.3, 15.1}
- Wider distribution of infectious and vector-borne pathogens {15.1, 26.1; Figure A4.16}
- Air quality worsened by smog, wildfire smoke, dust, and increased pollen {14.1, 14.2, 14.4, 23.1, 26.1}
- Threats to food and water security {11.2, 15.1}
- Mental and spiritual health stressors {15.1}



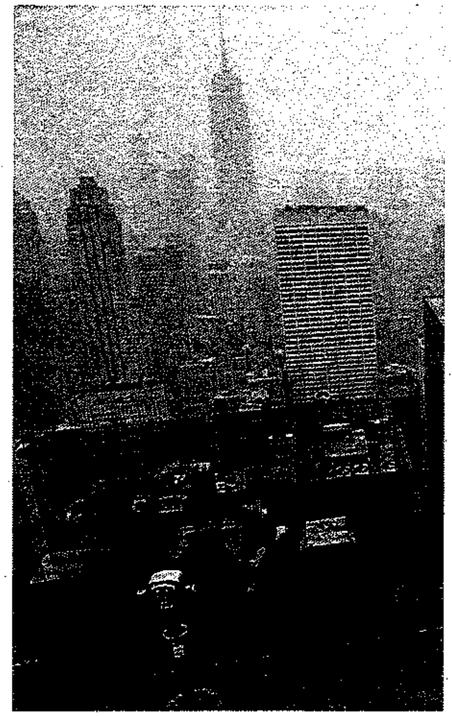


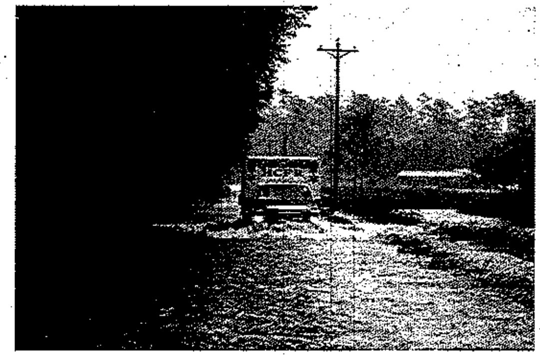
(**left**; Oregon) The Hooskanaden Landslide, triggered by heavy rainfall, caused substantial road damage. (**right**; Maunabo, Puerto Rico) Punta Tuna Wetlands Nature Reserve, which helps buffer the coastline from extreme events, was severely damaged during Hurricane Maria in 2017. Photo credits: (left) Oregon Department of Transportation [CC BY 2.0]; (right) Kenneth Wilsey, FEMA.

While climate change can harm everyone's health, its impacts exacerbate long-standing disparities that result in inequitable health outcomes for historically marginalized people, including people of color, Indigenous Peoples, low-income communities, and sexual and gender minorities, as well as older adults, people with disabilities or chronic diseases, outdoor workers, and children. {14.3, 15.2}

The disproportionate health impacts of climate change compound with similar disparities in other health contexts. For example, climate-related disasters during the COVID-19 pandemic, such as drought along the Colorado River basin, western wildfires, and Hurricane Laura, disproportionately magnified COVID-19 exposure, transmission, and disease severity and contributed to worsened health conditions for essential workers, older adults, farmworkers, low-wealth communities, and communities of color. {15.2; Focus on COVID-19 and Climate Change}

Large reductions in greenhouse gas emissions are expected to result in widespread health benefits and avoided death or illness that far outweigh the costs of mitigation actions. Improving early warning, surveillance, and communication of health threats; strengthening the resilience of healthcare systems; and supporting community-driven adaptation strategies can reduce inequities in the resources and capabilities needed to adapt as health threats from climate change continue to grow. {14.5, 15.3, 26.1, 30.2, 32.4}





(**left**; New York, New York) The Empire State Building is shrouded in a haze caused by smoke from the 2023 Canadian wildfires. (top right; Charleston, South Carolina) An ambulance drives through floodwaters. (bottom right; Atlanta, Georgia) Heatwaves in the Southeast are happening more frequently. Park amenities, such as trees and splash pads, help cool people on hot days. Photo credits: (left) Anthony Quintano [CC BY 2.0]; (top right) US Air National Guard photo by Tech. Sgt. Jorge Intriago; (bottom right) ucumari photography [CC BY-NC-ND 2.0]

Box 1.3. Indigenous Ways of Life and Spiritual Health

Indigenous communities, whose ways of life, cultures, intergenerational continuity, and spiritual health are tied to nature and the environment, are experiencing disproportionate health impacts of climate change. Rising temperatures and intensifying extreme events are reducing biodiversity and shifting the ranges of culturally important species like Pacific salmon, wild rice, and moose, making it more difficult for Indigenous Peoples to fish, hunt, and gather traditional and subsistence resources within Tribal jurisdictions. Heatwaves can prevent Tribal members from participating in traditional ceremonies, while flooding, erosion, landslides, and wildfires increasingly disrupt or damage burial grounds and ceremonial sites. {16.1, 15.2, 27.6}

Indigenous Peoples are leading numerous actions in response to climate change, including planning and policy initiatives, youth movements, cross-community collaborative efforts, and the expansion of renewable energy (Figure 1.11). Many of these efforts involve planning processes that start with place-based Indigenous Knowledge of local climate and ecosystems. {16.3}

Exemplifying Indigenous Resilience

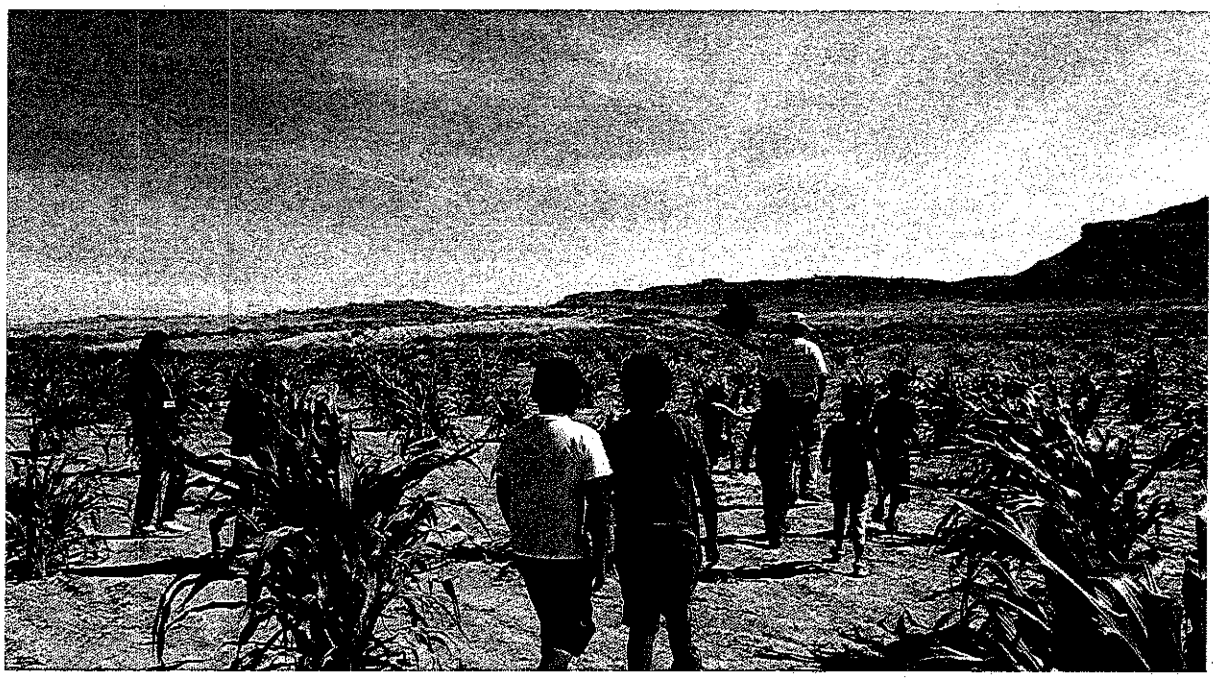
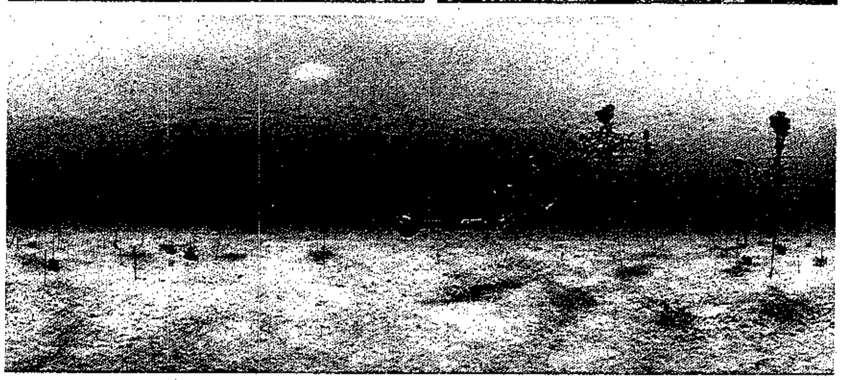


Figure 1.11. For over 2,000 years, the Hopi People have farmed on land with only 6–10 inches of annual precipitation. Today, Hopi children learn both the practices and process of Hopi dryland farming and the values, customs, and identities that underpin them. Photo credit: ©Michael K. Johnson. {Panel from Figure 16.6}

Ecosystems are undergoing transformational changes

Together with other stressors, climate change is harming the health and resilience of ecosystems, leading to reductions in biodiversity and ecosystem services. Increasing temperatures continue to shift habitat ranges as species expand into new regions or disappear from unfavorable areas, altering where people can hunt, catch, or gather economically important and traditional food sources. Degradation and extinction of local flora and fauna in vulnerable ecosystems like coral reefs and montane rainforests are expected in the near term, especially where climate changes favor invasive species or increase susceptibility to pests and pathogens. Without significant emissions reductions, rapid shifts in environmental conditions are expected to lead to irreversible ecological transformations by mid- to late century. {2.3, 6.2, 7.1, 7.2, 8.1, 8.2, 10.1, 10.2, 21.1, 24.2, 27.2, 28.5, 29.3, 29.5, 30.4; Figure A4.12}



Changes in ocean conditions and extreme events are already transforming coastal, aquatic, and marine ecosystems. Coral reefs are being lost due to warming and ocean acidification, harming important fisheries; coastal forests are converting to ghost forests, shrublands, and marsh due to sea level rise, reducing coastal protection; lake and stream habitats are being degraded by warming, heavy rainfall, and invasive species, leading to declines in economically important species. {8.1. 10.1, 21.2, 23.2, 24.2, 27.2; Figures 8.7, A4.11}

Increased risks to ecosystems are expected with further climate change and other environmental changes, such as habitat fragmentation, pollution, and overfishing. For example, mass fish die-offs from extreme summertime heat are projected to double by midcentury in northern temperate lakes under a very high scenario (RCP8.5). Continued climate changes are projected to exacerbate runoff and erosion, promote harmful algal blooms, and expand the range of invasive species. {4.2, 7.1, 8.2, 10.1, 21.2, 23.2, 24.2, 27.2, 28.2, 30.4}

While adaptation options to protect fragile ecosystems may be limited, particularly under higher levels of warming, management and restoration measures can reduce stress on ecological systems and build resilience. These measures include migration assistance for vulnerable species and protection of essential habitats, such as establishing wildlife corridors or places where species can avoid heat. Opportunities for nature-based solutions that assist in mitigation exist across the US, particularly those focused on protecting existing carbon sinks and increasing carbon storage by natural ecosystems. {8.3, 10.3, 23.2, 27.2; Focus on Blue Carbon}

(**top left**; Nags Head Woods, North Carolina) Coastal ghost forests result when trees are killed by sea level rise and saltwater intrusion. (**top right**; Molokai Island, Hawai'i) High island ecosystems are at risk due to invasive species, habitat destruction, intensifying fire, and drought. (**bottom**; Florida) A diver works on coral reef restoration around Florida Keys National Marine Sanctuary. Photo credits: (top left) NC Wetlands [CC BY 2.0]; (top right) Lucas Fortini, USGS; (bottom) Mitchell Tartt, NOAA.

Climate change slows economic growth, while climate action presents opportunities

With every additional increment of global warming, costly damages are expected to accelerate. For example, 2°F of warming is projected to cause more than twice the economic harm induced by 1°F of warming. Damages from additional warming pose significant risks to the US economy at multiple scales and can compound to dampen economic growth. {19.1}

- International impacts can disrupt trade, amplify costs along global supply chains, and affect domestic markets. {17.3, 19.2; Focus on Risks to Supply Chains}
- While some economic impacts of climate change are already being felt across the country, the impacts of future changes are projected to be more significant and apparent across the US economy. {19.1}
- States, cities, and municipalities confront climate-driven pressures on public budgets and borrowing costs amid spending increases on healthcare and disaster relief. {19.2}
- Household consumers face higher costs for goods and services, like groceries and health insurance premiums, as prices change to reflect both current and projected climate-related damages. {19.2}

Mitigation and adaptation actions present economic opportunities. Public and private measures—such as climate financial risk disclosures, carbon offset credit markets, and investments in green bonds—can avoid economic losses and improve property values, resilience, and equity. However, climate responses are not without risk. As innovation and trade open further investment opportunities in renewable energy and the country continues to transition away from fossil fuels, loss and disposal costs of stranded capital assets such as coal mines, oil and gas wells, and outdated power plants are expected. Climate solutions designed without input from affected communities can also result in increased vulnerability and cost burden. {17.3, 19.2, 19.3, 20.2, 20.3, 27.1, 31.6}

Many regional economies and livelihoods are threatened by damages to natural resources and intensifying extremes

Climate change is projected to reduce US economic output and labor productivity across many sectors, with effects differing based on local climate and the industries unique to each region. Climate-driven damages to local economies especially disrupt heritage industries (e.g., fishing traditions, trades passed down over generations, and cultural heritage–based tourism) and communities whose livelihoods depend on natural resources. {11.3, 19.1, 19.3}

- As fish stocks in the Northeast move northward and to deeper waters in response to rapidly rising ocean temperatures, important fisheries like scallops, shrimp, and cod are at risk. In Alaska, climate change has already played a role in 18 major fishery disasters that were especially damaging for coastal Indigenous Peoples, subsistence fishers, and rural communities. {10.2, 21.2, 29.3}
- While the Southeast and US Caribbean face high costs from projected labor losses and heat health risks to outdoor workers, small businesses are already confronting higher costs of goods and services and potential closures as they struggle to recover from the effects of compounding extreme weather events. {22.3, 23.1}
- Agricultural losses in the Midwest, including lower corn yields and damages to specialty crops like apples, are linked to rapid shifts between wet and dry conditions and stresses from climate-induced increases in pests and pathogens. Extreme heat and more intense wildfire and drought in the Southwest are already threatening agricultural worker health, reducing cattle production, and damaging wineries. {24.1, 28.5}
- In the Northern Great Plains, agriculture and recreation are expected to see primarily negative effects related to changing temperature and rainfall patterns. By 2070, the

Southern Great Plains is expected to lose cropland acreage as lands transition to pasture or grassland. {25.3, 26.2}

- Outdoor-dependent industries, such as tourism in Hawai'i and the US-Affiliated Pacific Islands and skiing in the Northwest, face significant economic loss from projected rises in park closures and reductions in workforce as continued warming leads to deterioration of coastal ecosystems and shorter winter seasons with less snowfall. {7.2, 8.3, 10.1, 10.3, 19.1, 27.3, 30.4}

Mitigation and adaptation actions taken by businesses and industries promote resilience and offer long-term benefits to employers, employees, and surrounding communities. For example, as commercial fisheries adapt, diversifying harvest and livelihoods can help stabilize income or buffer risk. In addition, regulators and investors are increasingly requiring businesses to disclose climate risks and management strategies. {10.2, 19.3, 26.2}

Scarlett W.

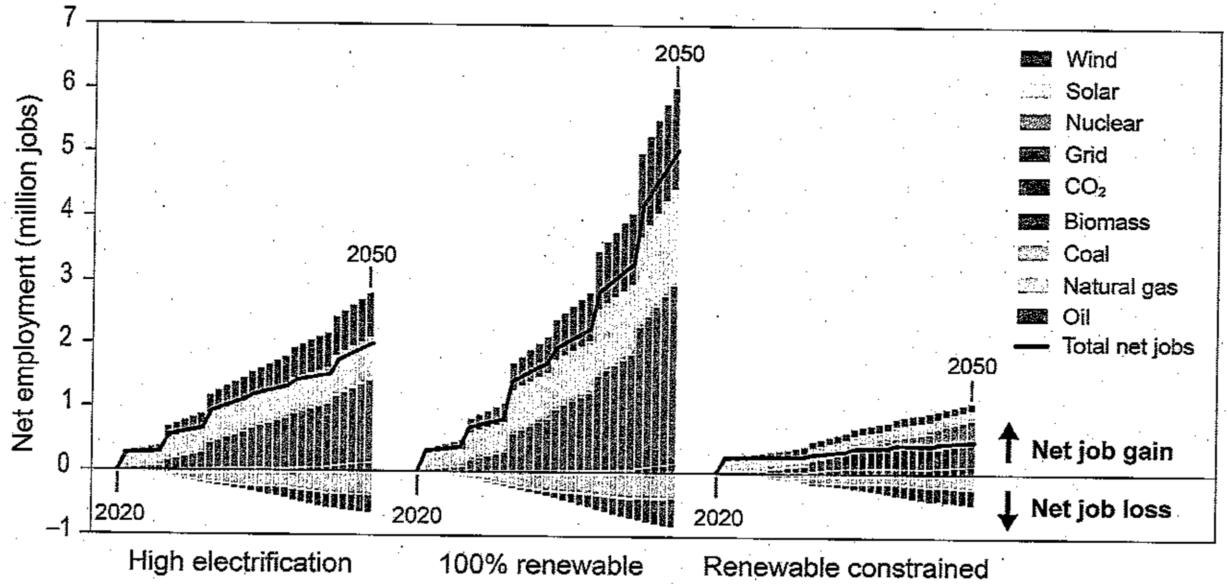
(**top left**; Fort Myers Beach, Florida) Shops and restaurants were severely damaged or completed destroyed by Hurricane Ian in 2022. (**bottom left**; Whatcom County, Washington) Snow-based recreational industries, such as skiing in the Pacific Northwest, are projected to lose revenue due to declining snowpack. (**right**; Maine) A causeway connecting Little Deer Isle to Deer Isle (the largest lobster port in the state) is threatened by sea level rise. Photo credits: (top left) Coast Guard Petty Officer 3rd Class Gabriel Wisdom; (bottom left) US Forest Service–Pacific Northwest Region; (right) ©Jack Sullivan, Island Institute.

Job opportunities are shifting due to climate change and climate action

Many US households are already feeling the economic impacts of climate change. Climate change is projected to impose a variety of new or higher costs on most households as healthcare, food, insurance, building, and repair costs become more expensive. Compounding climate stressors can increase segregation, income inequality, and reliance on social safety net programs. Quality of life is also threatened by climate change in ways that can be more difficult to quantify, such as increased crime and domestic violence, harm to mental health, reduced happiness, and fewer opportunities for outdoor recreation and play. {11.3, 19.1, 19.3}

Climate change, and how the country responds, is expected to alter demand for workers and shift where jobs are available. For example, energy-related livelihoods in the Northern and Southern Great Plains are expected to shift as the energy sector transforms toward more renewables, low-carbon technologies, and electrification of more sectors of the economy. Losses in fossil fuel–related jobs are projected to be completely offset by greater increases in mitigation-related jobs, as increased demand for renewable energy and low-carbon technologies is expected to lead to long-term expansion in most states' energy and decarbonization workforce (Figure 1.12). Grid expansion and energy efficiency efforts are already creating new jobs in places like Nevada, Vermont, and Alaska, and advancements in biofuels and agrivoltaics (combined renewable energy and agriculture) provide economic opportunities in rural communities. {10.2, 11.3, 19.3, 25.3, 26.2, 29.3, 32.4}

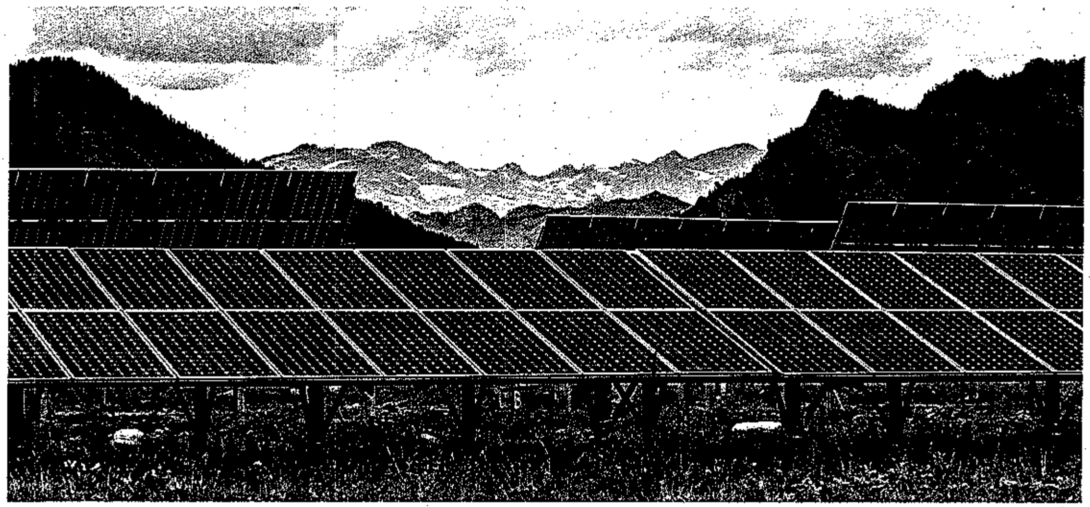
Additional opportunities include jobs in ecosystem restoration and construction of energy-efficient and climate-resilient housing and infrastructure. Workforce training and equitable access to clean energy jobs, which have tended to exclude women and people of color, are essential elements of a just transition to a decarbonized economy. {5.3, 19.3, 20.3, 22.3, 25.3, 26.2, 27.3, 32.4}

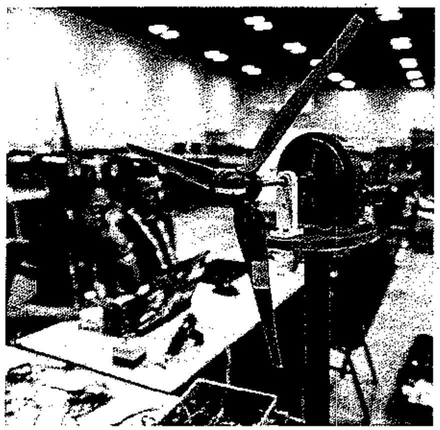


Energy Employment (2020–2050) for Alternative Net-Zero Pathways

Employment gains in electrification and renewable energy industries are projected to far outpace job losses in fossil fuel industries.

Figure 1.12. Despite decreases in the number of fossil fuel–related jobs, the overall number of energy jobs (specifically those involved in the supply of energy) relative to 2019 is generally projected to increase in net-zero-emissions energy scenarios between 2020 and 2050, although by much more in some scenarios than in others. {Figure 32.17} Adapted with permission from Jenkins et al. 2021.





(**top**; Golden, Colorado) Solar panels are pictured on the campus of the National Renewable Energy Laboratory. (**bottom left**; San Antonio, Texas) Participants in the 2022 Collegiate Wind Competition focus on offshore wind projects. (**bottom right**; Lexington, Virginia) Workers install fiber-optic cables. Rural broadband deployment is associated with higher incomes and lower unemployment rates. Photo credits: (top and bottom left) Werner Slocum/NREL [CC-BY-NC-ND 2.0]; (bottom right) Preston Keres, USDA

Climate change is disrupting cultures, heritages, and traditions

As climate change transforms US landscapes and ecosystems, many deeply rooted community ties, pastimes, Traditional Knowledges, and cultural or spiritual connections to place are at risk. Cultural heritage—including buildings, monuments, livelihoods, and practices—is threatened by impacts on natural ecosystems and the built environment. Damages to archaeological, cultural, and historical sites further reduce opportunities to transfer important knowledge and identity to future generations. {6.1, 7.2, 8.3, 9.2, 10.1, 12.2, 16.1, 22.1, 23.1, 26.1, 27.6, 28.2; Introductions in Chs. 10, 30}

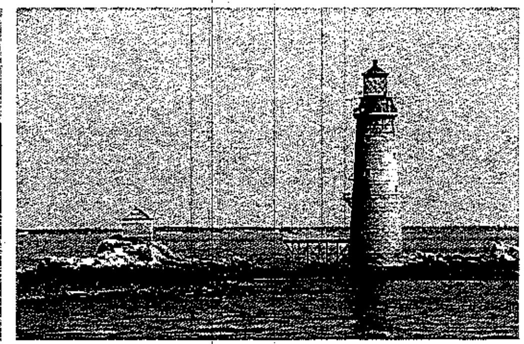
Many outdoor activities and traditions are already being affected by climate change, with overall impacts projected to further hinder recreation, cultural practices, and the ability of communities to maintain local heritage and a sense of place. {19.1}

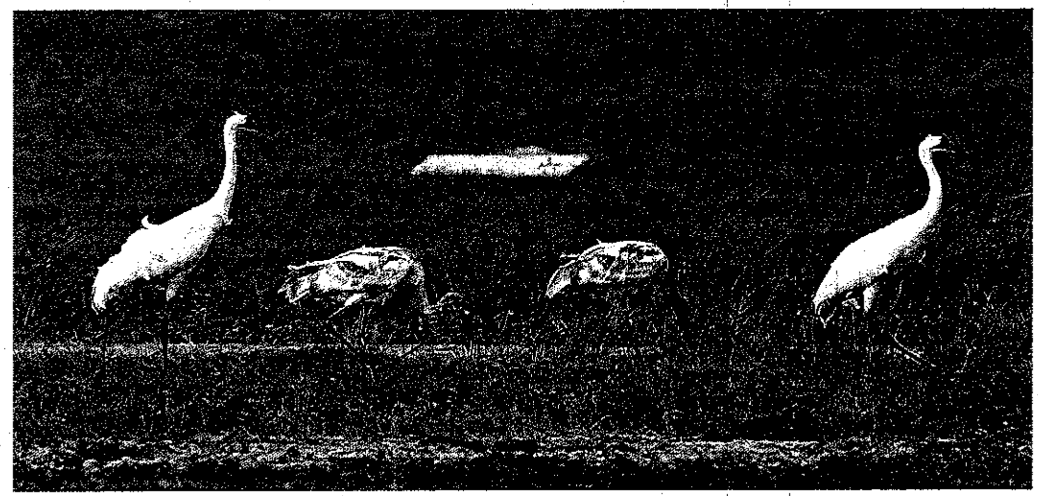
For example:

- The prevalence of invasive species and harmful algal blooms is increasing as waters warm, threatening activities like swimming along Southeast beaches, boating and fishing for walleye in the Great Lakes, and viewing whooping cranes along the Gulf Coast. In the Northwest, water-based recreation demand is expected to increase in spring and summer months, but reduced water quality and harmful algal blooms are expected to restrict these opportunities. {24.2, 24.5, 26.3, 27.6}

- Ranges of culturally important species are shifting as temperatures warm, making them harder to find in areas where Indigenous Peoples have access (see Box 1.3). {11.2, 24.2, 26.1}
- Hikers, campers, athletes, and spectators face increasing threats from more severe heatwaves, wildfires, and floods and greater exposure to infectious disease. {15.1, 22.2, 26.3, 27.6}

Nature-based solutions and ecosystem restoration can preserve cultural heritage while also providing valuable local benefits, such as flood protection and new recreational opportunities. Cultural heritage can also play a key role in climate solutions, as incorporating local values, Indigenous Knowledge, and equity into design and planning can help reaffirm a community's connection to place, strengthen social networks, and build new traditions. {7.3, 26.1, 26.3, 30.5}





(**top left**; Glacier National Park, Montana) Wildfire smoke jeopardizes participation in outdoor sports and recreation. (**top right**; Boston Harbor, Massachusetts) Sea level rise threatens historical and archaeological sites on the Boston Harbor Islands. (**bottom**; Goose Island, Texas) Whooping cranes, which draw birdwatchers to the Gulf of Mexico, are at risk due to flooding, drought, and upstream water use. Photo credit: (top left) Andrew Parlette [CC BY 2.0]; (top right) cmh2315fl [CC BY-NC 2.0]; (bottom) Alan Schmierer [CC0 1.0].

The Choices That Will Determine the Future

With each additional increment of warming, the consequences of climate change increase. The faster and further the world cuts greenhouse gas emissions, the more future warming will be avoided, increasing the chances of limiting or avoiding harmful impacts to current and future generations.

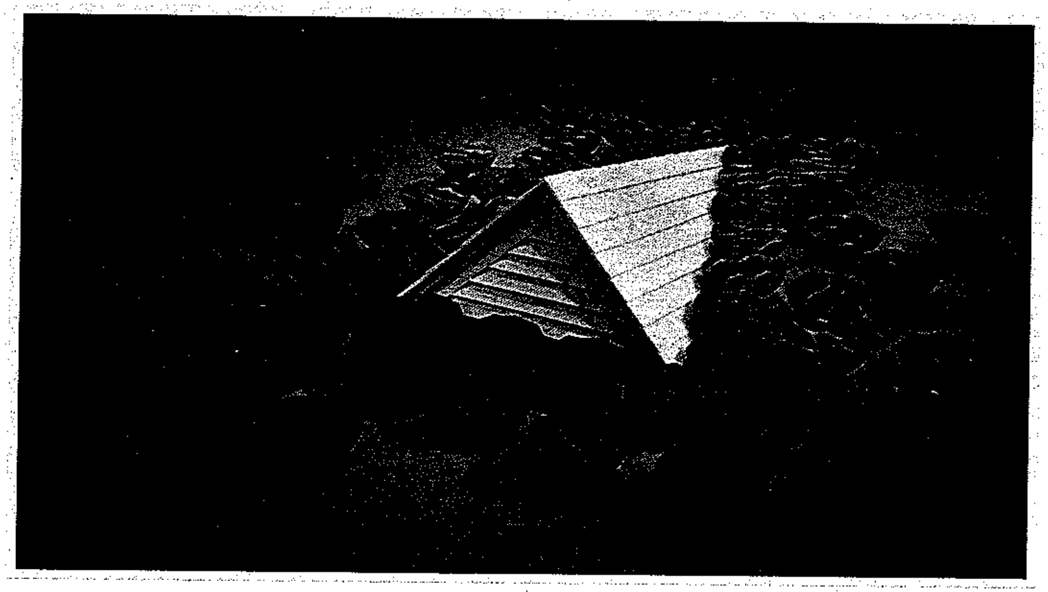
Societal choices drive greenhouse gas emissions

The choices people make on a day-to-day basis—how to power homes and businesses, get around, and produce and use food and other goods—collectively determine the amount of greenhouse gases emitted. Human use of fossil fuels for transportation and energy generation, along with activities like manufacturing and agriculture, has increased atmospheric levels of carbon dioxide (CO_2) and other heat-trapping greenhouse gases. Since 1850, CO_2 concentrations have increased by almost 50%, methane by more than 156%, and nitrous oxide by 23%, resulting in long-term global warming. {2.1, 3.1; Ch. 2, Introduction}

The CO_2 not removed from the atmosphere by natural sinks lingers for thousands of years. This means that CO_2 emitted long ago continues to contribute to climate change today. Because of historical trends, cumulative CO_2 emissions from fossil fuels and industry in the US are higher than from any other country. To understand the total contributions of past actions to observed climate change, additional warming from CO_2 emissions from land use, land-use change, and forestry, as well as emissions of nitrous oxide and the shorter-lived greenhouse gas methane, should also be taken into account. Accounting for all of these factors and emissions from 1850–2021, emissions from the US are estimated to comprise approximately 17% of current global warming. {2.1}

Tami Phelps

Carbon dioxide, along with other greenhouse gases like methane and nitrous oxide, is well-mixed in the atmosphere. This means these gases warm the planet regardless of where they were emitted. For the first half of the 20th century, the vast majority of greenhouse gas emissions came from the US and Europe. But as US and European emissions have been falling (US emissions in 2021 were 17% lower than 2005 levels), emissions from the rest of the world, particularly Asia, have been rising rapidly. The choices the US and other countries make now will determine the trajectory of climate change and associated impacts for many generations to come (Figure 1.13). {2.1, 2.3; Ch. 32}



George Lorio

Box 1.4. Global Warming Levels

Because long-term societal actions are uncertain, climate modeling experts use different scenarios of plausible futures to represent a range of possible trajectories. These scenarios capture variables such as the relationship between human behavior, greenhouse gas emissions, Earth's responses to changes in the concentration of greenhouse gases in our atmosphere and ocean, and the resulting impacts, including temperature change and sea level rise. {3.3; Guide to the Report; App. 3}

Since there are uncertainties inherent in all of these factors—especially human behavior and the choices that determine emissions levels—the resulting range of projections are not predictions but instead reflect multiple potential future pathways. Future climate change under a given scenario is often expressed in one of two ways: as a range of potential outcomes in a future year (Figure 1.13a) or the time at which a specific outcome is expected (Figure 1.13b). {2.3, 3.3; App. 3}

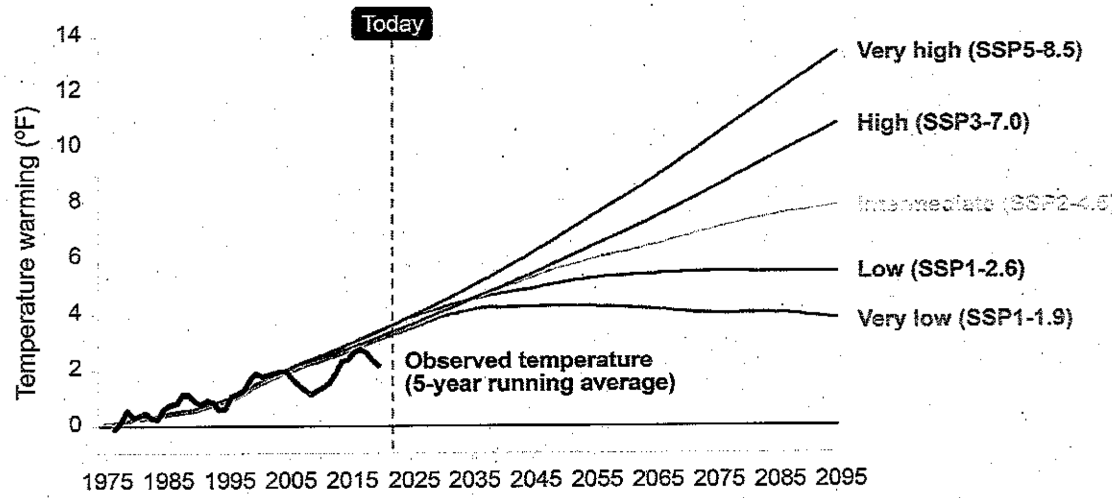
Over the next decade, projected global warming is very similar across all scenarios. Updating energy infrastructure or making systemic economic and political changes takes time, thus temperature trajectories under different scenarios take time to diverge. {2.3}

By midcentury (2040–2070), differences between projected temperatures under higher and lower scenarios become apparent. By the end of the century, the global warming level—that is, how much the global average surface temperature increases above preindustrial levels—is expected to exceed 5.4°F (3°C) under high and very high scenarios (SSP3-7.0 and SSP5-8.5, respectively), and the world could see more than 7.2°F (4°C) of warming under a very high scenario (SSP5-8.5). Long-term global warming is expected to stay below 3.6°F (2°C) under a low scenario (SSP1-2.6) and can be limited to 2.7°F (1.5°C) only under a very low scenario (SSP1-1.9). {2.3}

The risk of exceeding a particular global warming level depends on future emissions. This means that projections are conditional: when or if the world reaches a particular level of warming is largely dependent on human choices. {2.3}

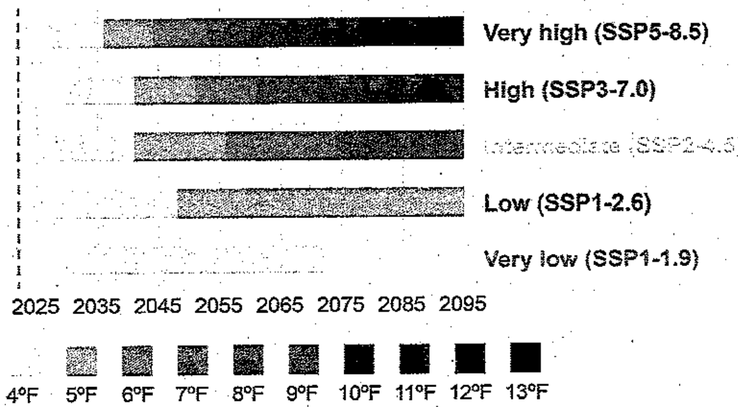
Future Warming

Future warming in the United States will depend on the total amount of global greenhouse gas emissions.



Crossing Times

Whether–and when–a given temperature threshold is crossed depends on both the amount and rate of global greenhouse gas emissions.



Potential Warming Pathways in the United States

When or if the US reaches a particular level of warming depends on global greenhouse gas emissions from human activities.

Figure 1.13. How much warming the US will experience—and when a given temperature threshold is crossed—depends on future global emissions. The **top graph** shows observed change in US surface temperature during 1975–2022 (black line, 5-year averaged) and modeled historical (1975–2014) and projected (2015–2095) change in surface temperature compared to 1951–1980, annually averaged over all 50 states and Puerto Rico under different climate scenarios (multicolored lines; see Table 3 in the Guide to the Report). The **bottom graph** shows the same projections in a different way, highlighting the year in which the US crosses temperature thresholds under each scenario. The vertical dashed line represents the year 2023. Data for the US-Affiliated Pacific Islands and the US Virgin Islands are not available. See Figure 1.5 for observed US and global temperature changes since 1895. Adapted with permission from Figure TS.1 in Arias et al. 2021.

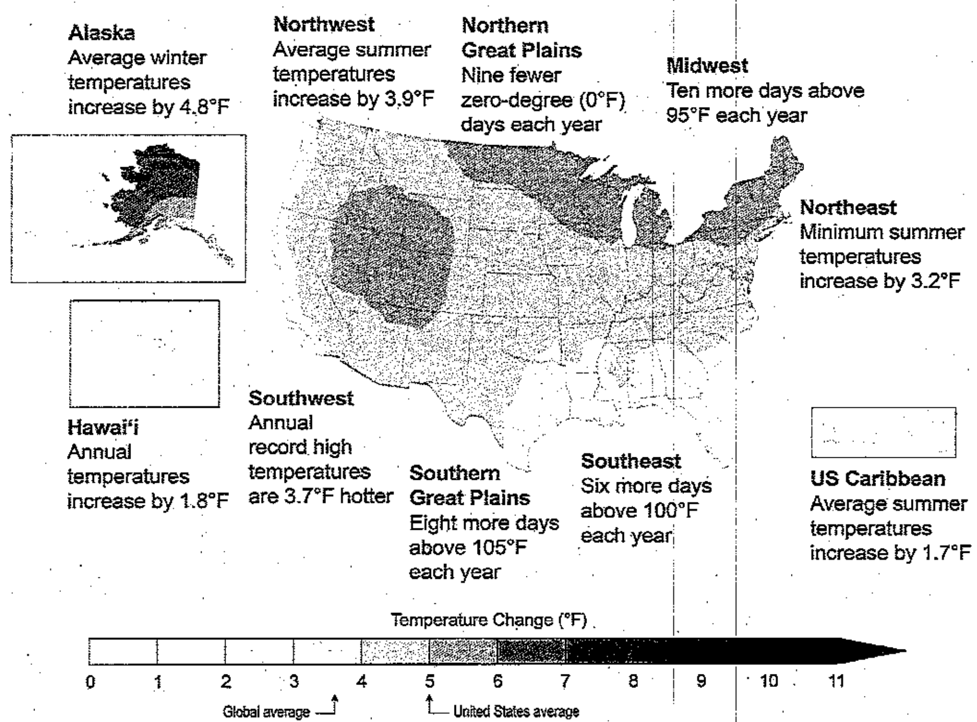
Rising global emissions are driving global warming, with faster warming in the US

The observed global warming of about 2°F (1.1°C) over the industrial era is unequivocally caused by greenhouse gas emissions from human activities, with only very small effects from natural sources. About three-quarters of total emissions and warming (1.7°F [0.95°C]) have occurred since 1970. Warming would have been even greater without the land and ocean carbon sinks, which have absorbed more than half of the CO_2 emitted by humans. {2.1, 3.1, 7.2; Ch. 2, Introduction; Figures 3.1, 3.8}

The US is warming faster than the global average, reflecting a broader global pattern: land areas are warming faster than the ocean, and higher latitudes are warming faster than lower latitudes. Additional global warming is expected to lead to even greater warming in some US regions, particularly Alaska (Figure 1.14). {2.1, 3.4; Ch. 2, Introduction; App. 4}

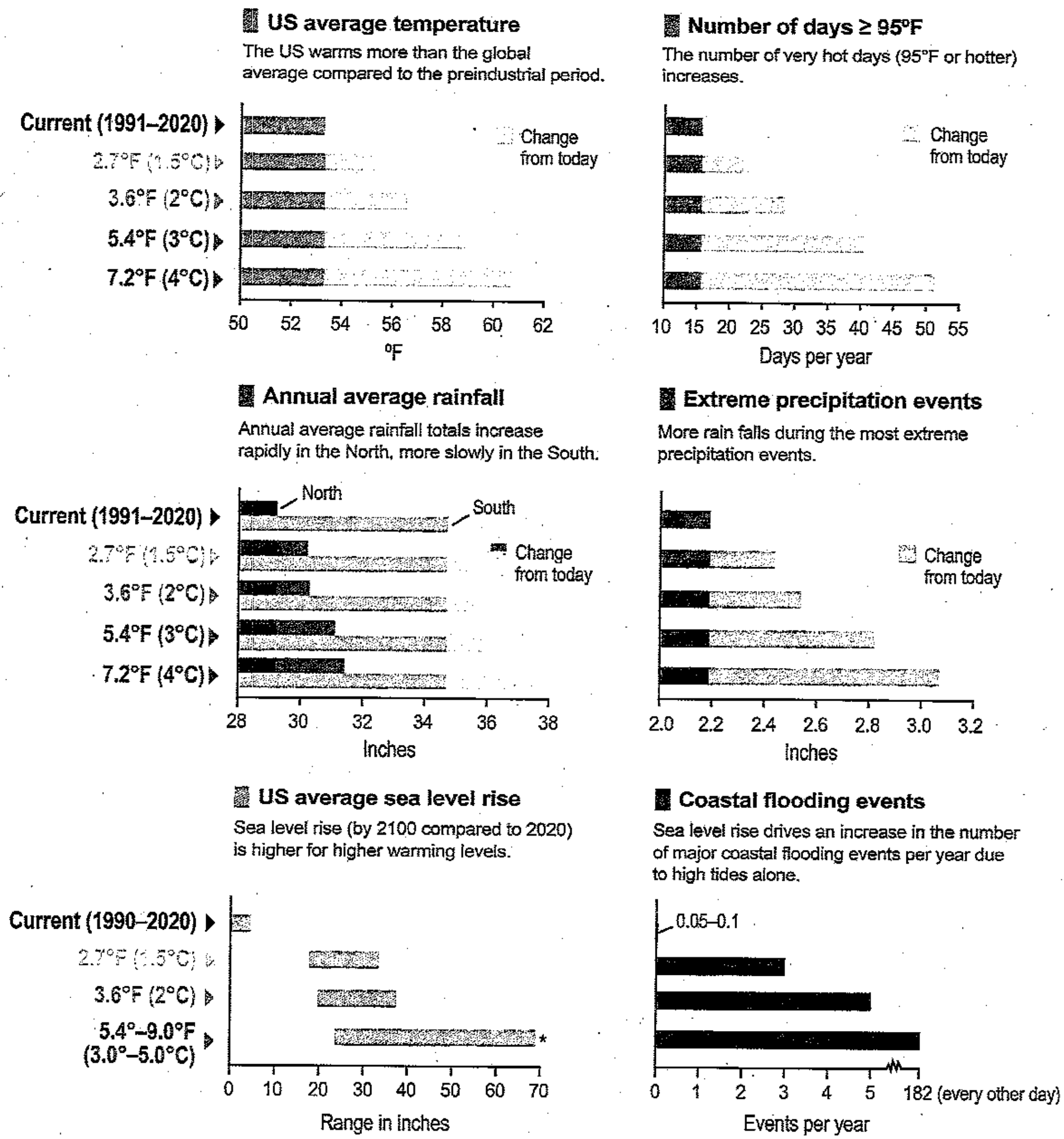
Warming increases risks to the US

Rising temperatures lead to many large-scale changes in Earth's climate system, and the consequences increase with warming (Figure 1.15). Some of these changes can be further amplified through feedback processes at higher levels of warming, increasing the risk of potentially catastrophic outcomes. For example, uncertainty in the stability of ice sheets at high warming levels means that increases in sea level along the continental US of 3–7 feet by 2100 and 5–12 feet by 2150 are distinct possibilities that cannot be ruled out. The chance of reaching the upper end of these ranges increases as more warming occurs. In addition to warming more, the Earth warms faster in high and very high scenarios (SSP3-7.0 and SSP5-8.5, respectively), making adaptation more challenging. {2.3, 3.1, 3.4, 9.1}



What would 3.6°F (2°C) of global warming feel like in the United States?

Figure 1.14. As the world warms, the United States warms more on average. The map shows projected changes in annual surface temperature compared to the present day (1991–2020) under a global warming level of 3.6°F (2°C) above preindustrial levels (see Figure 2.9). Regional examples show how different temperature impacts would be experienced across the country at this level of warming. Figure credit: USGCRP, NOAA NCEI, and CISESS NC.



*Rise at the upper end of this range cannot be ruled out due to the possibility of rapid ice sheet loss. The amount of warming required to trigger such loss is not currently known but is assessed to be above 3.6°F (2°C).

Consequences Are Greater at Higher Global Warming Levels

At higher global warming levels, the US will experience more severe climate impacts.

Figure 1.15. With each additional increment of global warming, climate impacts in the US are projected to be more severe: US average temperature warms more than the global average (**top left**), and the number of days per year at or above 95°F in the US increases (**top right**). Annual average US rainfall increases rapidly in the North and more slowly in the South (**center left**), and more rain falls during the most extreme precipitation events (**center right**). Sea level rise (range of projected increases by 2100 compared to 2020) is higher (**bottom left**), driving an increase in the number of major coastal flooding events per year due to high tides alone (**bottom right**). Temperature (averages and extremely hot days; top row) and extreme rainfall projections (center right) are averages for all 50 states and Puerto Rico. Average rainfall projections (center left) are shown for both the northern and southern US (above and below 37° latitude, respectively). Sea level rise (bottom left) and coastal flooding (bottom right) projections are averages for the contiguous United States. For sea level change estimates outside of the contiguous US, see Chapter 23 (for Puerto Rico and the US Virgin Islands), Chapter 30 (for Hawai'i and the US-Affiliated Pacific Islands), and Sweet et al. 2022 (for Alaska). Global warming levels refer to warming since preindustrial temperature conditions, defined as the 1851–1900 average. Figure credit: USGCRP, NOAA NOS, NASA, NOAA NCEI, and CISESS NC.

How Climate Action Can Create a More Resilient and Just Nation

Large near-term cuts in greenhouse gas emissions are achievable through many currently available and cost-effective mitigation options. However, reaching net-zero emissions by midcentury cannot be achieved without exploring additional mitigation options. Even if the world decarbonizes rapidly, the Nation will continue to face climate impacts and risks. Adequately and equitably addressing these risks involves longer-term inclusive planning, investments in transformative adaptation, and mitigation approaches that consider equity and justice.

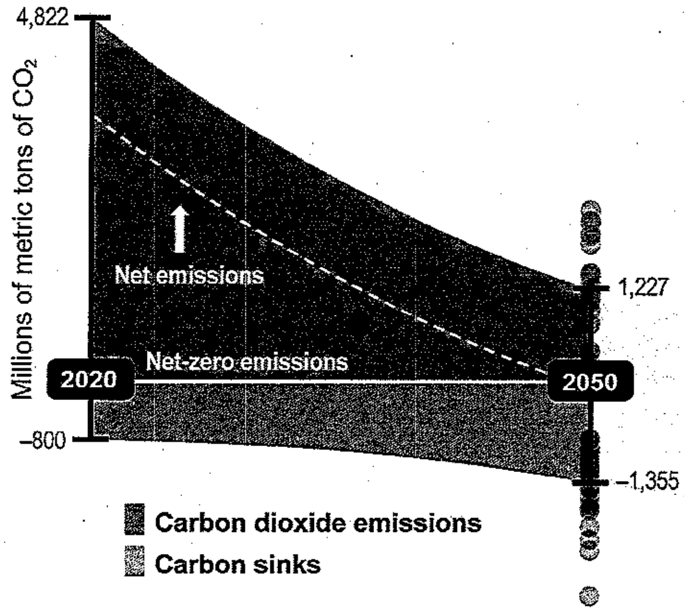
Available mitigation strategies can deliver substantial emissions reductions, but additional options are needed to reach net zero

Limiting global temperature change to well below 2°C (3.6°F) requires reaching net-zero CO_2 emissions globally by 2050 and net-zero emissions of all greenhouse gases from human activities within the following few decades (see "Meeting US mitigation targets means reaching net-zero emissions" above). Net-zero emissions pathways involve widespread implementation of currently available and cost-effective options for reducing emissions alongside rapid expansion of technologies and methods to remove carbon from the atmosphere to balance remaining emissions. However, to reach net-zero emissions, additional mitigation options need to be explored (Figure 1.16). Pathways to net zero involve large-scale technological, infrastructure, land-use, and behavioral changes and shifts in governance structures. {5.3, 6.3, 9.2, 9.3, 10.4, 13.2, 16.2, 18.4, 20.1, 24.1, 25.5, 30.5, 32.2, 32.3; Focus on Blue Carbon}

Scenarios that reach net-zero emissions include some of the following key options:

- Decarbonizing the electricity sector, primarily through expansion of wind and solar energy, supported by energy storage {32.2}
- Transitioning to transportation and heating systems that use zero-carbon electricity or low-carbon fuels, such as hydrogen {5.3, 13.1, 32.2, 32.3}
- Improving energy efficiency in buildings, appliances, and light- and heavy-duty vehicles and other transportation modes {5.3, 13.3, 32.2}
- Implementing urban planning and building design that reduces energy demands through more public transportation and active transportation and lower cooling demands for buildings {12.3, 13.1, 32.2}
- Increasing the efficiency and sustainability of food production, distribution, and consumption {11.1, 32.2}
- Improving land management to decrease greenhouse gas emissions and increase carbon removal and storage, with options ranging from afforestation, reforestation, and restoring coastal ecosystems to industrial processes that directly capture and store carbon from the air {5.3, 6.3, 8.3, 32.2, 32.3; Focus on Blue Carbon}

Portfolio of Mitigation Options for Achieving Net Zero by 2050



Reducing Emissions

Established opportunities

- Improved energy efficiency
- Decarbonized electricity generation
- Electrified energy end uses
- Improved efficiency of agricultural and food systems

Additional opportunities

- Hydrogen and other low-carbon fuels
- Carbon capture and storage
- Long-duration energy storage
- Energy demand management

Increasing Carbon Uptake

Established opportunities

- Nature-based solutions that remove and store carbon, such as:
  - Improved cropland and pasture management
  - Avoided conversion of unmanaged lands
  - Afforestation and reforestation

Additional opportunities

- Additional nature-based solutions, such as ocean carbon dioxide removal or blue carbon
- Biomass energy with carbon capture and storage
- Technological direct air capture

Reaching net zero by 2050 in the US will involve a mix of reductions in greenhouse gas emissions and increases in carbon dioxide removal.

Figure 1.16. Reaching net-zero emissions (horizontal white line) by midcentury in the US would mean deep reductions in emissions of carbon dioxide (CO_2) and other greenhouse gases (**top side of figure**; red), with residual emissions balanced by additional removal of CO_2 from the atmosphere (**bottom side of figure**; blue). The dashed white line shows net emissions to the atmosphere (the sum of carbon sources and carbon sinks). The dots at 2050 show ranges of emissions and uptake for energy model scenarios explored in detail in Chapter 32. Model scenarios that achieve these targets project a mix of established opportunities for reducing emissions and increasing carbon sinks. Among these, energy efficiency, decarbonized electricity (mainly renewables), and end-use electrification are critical for the energy sector. While not exhaustive, the list also includes additional opportunities, many of which are emerging technologies that will be integral to reaching net zero. These include options like use of hydrogen and low-carbon fuels to further reduce emissions in difficult-to-decarbonize sectors and greatly increasing CO_2 removal. Figure credit: EPA; University of California, Irvine; NOAA NCEI; and CISESS NC.

Due to large declines in technology and deployment costs over the last decade (Figure 1.2), decarbonizing the electricity sector is expected to be largely driven by rapid growth in renewable energy. Recent legislation is also expected to increase deployment rates of low- and zero-carbon technology. To reach net-zero targets, the US will need to add new electricity-generating capacity, mostly wind and solar, faster than ever before. This infrastructure expansion may drastically increase demand for products (batteries, solar photovoltaics) and resources, such as metals and critical minerals. Near-term shortages in minerals and metals due to increased demand can be addressed by increased recycling, for example, which can also reduce dependence on imported materials. {5.2, 5.3, 17.2, 25.3, 32.2, 32.4; Focus on Risks to Supply Chains}

Most US net-zero scenarios require CO_2 removal from the atmosphere to balance residual emissions, particularly from sectors where decarbonization is difficult. In these scenarios, nuclear and hydropower capacity are maintained but not greatly expanded; natural gas-fired generation declines, but more slowly if coupled with carbon capture and storage. {32.2}

Nature-based solutions that restore degraded ecosystems and preserve or enhance carbon storage in natural systems like forests, oceans, and wetlands, as well as agricultural lands, are cost-effective mitigation strategies. For example, with conservation and restoration, marine and coastal ecosystems could capture and store enough atmospheric carbon each year to offset about 3% of global emissions (based on 2019 and 2020 emissions). Many nature-based solutions can provide additional benefits, like improved ecosystem resilience, food production, improved water quality, and recreational opportunities. {8.3; Boxes 7.2, 32.2; Focus on Blue Carbon}

Adequately addressing climate risks involves transformative adaptation

While adaptation planning and implementation has advanced in the US, most adaptation actions to date have been incremental and small in scale (see Table 1.3). In many cases, more transformative adaptation will be necessary to adequately address the risks of current and future climate change. {31.1, 31.3}.

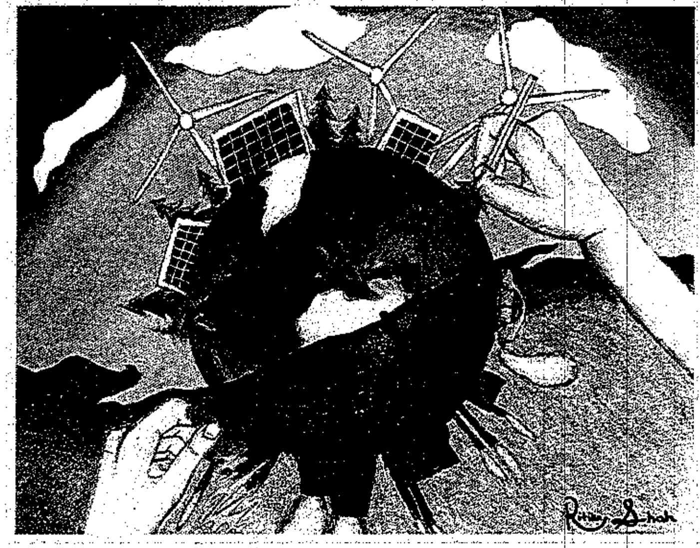
Table 1.3. Incremental Versus Transformative Adaptation Approaches

	Examples of incremental adaptation	Examples of transformative adaptation
	Using air-conditioning during heatwaves	Redesigning cities and buildings to address heat
	Reducing water consumption during droughts	Shifting water-intensive industry to match projected rainfall patterns
	Elevating homes above flood waters	Directing new housing development to less flood-prone areas

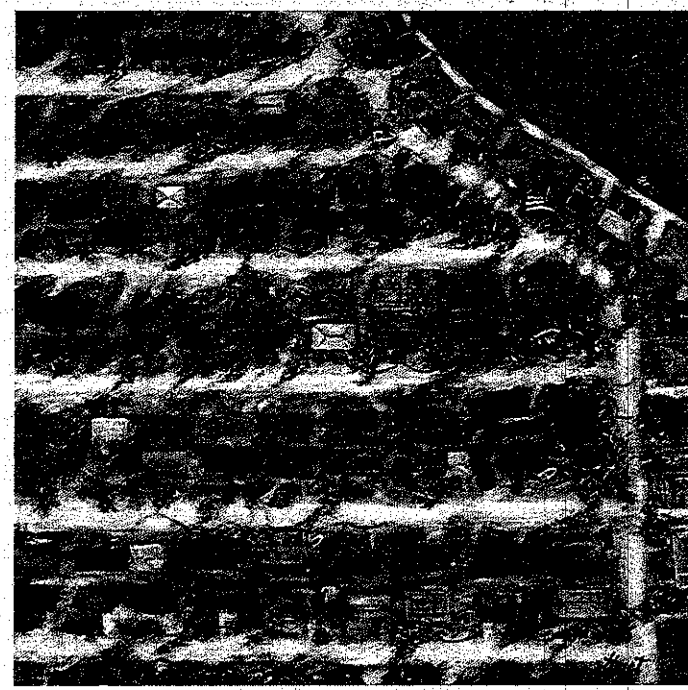
Transformative adaptation involves fundamental shifts in systems, values, and practices, including assessing potential trade-offs, intentionally integrating equity into adaptation processes, and making systemic changes to institutions and norms. While barriers to adaptation remain, many of these can be overcome with financial, cultural, technological, legislative, or institutional changes. {31.1, 31.2, 31.3}.

Adaptation planning can more effectively reduce climate risk when it identifies not only disparities in how people are affected by climate change but also the underlying causes of climate vulnerability. Transformative adaptation would involve consideration of both the physical and social drivers of vulnerability and how they interact to shape local experiences of vulnerability and disparities in risk. Examples include understanding how differing levels of access to disaster assistance constrain recovery outcomes or how disaster damage exacerbates long-term wealth inequality. Effective adaptation, both incremental and transformative, involves developing and investing in new monitoring and evaluation methods to understand the different values of, and impacts on, diverse individuals and communities. {9.3, 19.3, 31.2, 31.3, 31.5}

Transformative adaptation would require new and better-coordinated governance mechanisms and cooperation across all levels of government, the private sector, and society. A coordinated, systems-based approach can support consideration of risks that cut across multiple sectors and scales, as well as the development of context-specific adaptations. For example, California, Florida, and other states have used informal regional collaborations to develop adaptation strategies tailored to their area. Adaptation measures that are designed and implemented using inclusive, participatory planning approaches and leverage coordinated governance and financing have the greatest potential for long-term benefits, such as improved quality of life and increased economic productivity. {10.3, 18.4, 20.2, 31.4}



Ritika S.



Joan Hart

Mitigation and adaptation actions can result in systemic, cascading benefits

Actions taken now to accelerate net emissions reductions and adapt to ongoing changes can reduce risks to current and future generations. Mitigation and adaptation actions, from international to individual scales, can also result in a range of benefits beyond limiting harmful climate impacts, including some immediate benefits (Figure 1.1). The benefits of mitigation and proactive adaptation investments are expected to outweigh the costs. {2.3, 13.3, 14.5, 15.3, 17.4, 22.1, 31.6, 32.4; Introductions in Chs. 17, 31}

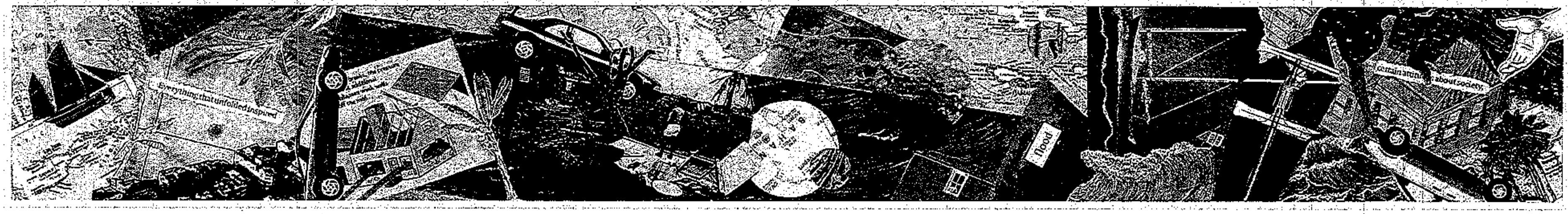
- Accelerating the deployment of low-carbon technologies, expanding renewable energy, and improving building efficiency can have significant near-term social and economic benefits like reducing energy costs and creating jobs. {32.4}
- Transitioning to a carbon-free, sustainable, and resilient transportation system can lead to improvements in air quality, fewer traffic fatalities, lower costs to travelers, improved mental and physical health, and healthier ecosystems. {13.3}
- Reducing emissions of short-lived climate pollutants like methane, black carbon, and ozone provides immediate air quality benefits that save lives and decrease the burden on healthcare systems while also slowing near-term warming. {11.1, 14.5, 15.3}
- Green infrastructure and nature-based solutions that accelerate pathways to net-zero emissions through restoration and protection of ecological resources can improve water quality, strengthen biodiversity, provide protection from climate hazards like heat extremes or flooding, preserve cultural heritage and traditions, and support more equitable access to environmental amenities. {8.3, 15.3, 20.3, 24.4, 30.4; Focus on Blue Carbon}
- Strategic planning and investment in resilience can reduce the economic impacts of climate change, including costs to households and businesses, risks to markets and supply chains, and potential negative impacts on employment and income, while also providing opportunities for economic gain. {9.2, 19.3, 26.2, 31.6; Focus on Risks to Supply Chains}
- Improving cropland management and climate-smart agricultural practices can strengthen the resilience and profitability of farms while also increasing soil carbon uptake and storage, reducing emissions of nitrous oxide and methane, and enhancing agricultural efficiency and yields. {11.1, 24.1, 32.2}

Climate actions that incorporate inclusive and sustained engagement with overburdened and underserved communities in the design, planning, and implementation of evidence-based strategies can also reduce existing disparities and address social injustices. {24.3, 31.2, 32.4}

Transformative climate actions can strengthen resilience and advance equity

Fossil fuel-based energy systems have resulted in disproportionate public health burdens on communities of color and/or low-income communities. These same communities are also disproportionately harmed by climate change impacts. {13.4, 15.2, 32.4}

A "just transition" is the process of responding to climate change with transformative actions that address the root causes of climate vulnerability while ensuring equitable access to jobs; affordable, low-carbon energy; environmental benefits such as reduced air pollution; and quality of life for all. This involves reducing impacts to overburdened communities, increasing resources to underserved communities, and integrating diverse worldviews, cultures, experiences, and capacities into mitigation and adaptation actions. As the country shifts to low-carbon energy industries, a just transition would include job creation and training for displaced fossil fuel workers and addressing



Melanie Mills

existing racial and gender disparities in energy workforces. For example, Colorado agencies are creating plans to guide the state's transition away from coal, with a focus on economic diversification, job creation, and workforce training for former coal workers. The state's plan also acknowledges a commitment to communities disproportionately impacted by coal power pollution. {5.3, 13.4, 14.3, 15.2, 16.2, 20.3, 31.2, 32.4; Figure 20.1}

A just transition would take into account key aspects of environmental justice:

- Recognizing that certain people have borne disparate burdens related to current and historical social injustices and, thus, may have different needs
- Ensuring that people interested in and affected by outcomes of decision-making processes are included in those procedures through fair and meaningful engagement
- Distributing resources and opportunities over time, including access to data and information, so that no single group or set of individuals receives disproportionate benefits or burdens

{20.3; Figure 20.1}

An equitable and sustainable US response to climate change has the potential to reduce climate impacts while improving well-being, strengthening resilience, benefiting the economy, and, in part, redressing legacies of racism and injustice. Transformative adaptation and the transition to a net-zero energy system come with challenges and trade-offs that would need to be considered to avoid exacerbating or creating new social injustices. For example, transforming car-centric transportation systems to emphasize public transit and walkability could increase accessibility for underserved communities and people with limited mobility—if user input and equity are intentionally considered. {13.4, 20.3, 31.3, 32.4; Ch. 31, Introduction}

Equitable responses that assess trade-offs strengthen community resilience and self-determination, often fostering innovative solutions. Engaging communities in identifying challenges and bringing together diverse voices to participate in decision-making allows for more inclusive, effective, and transparent planning processes that account for the structural factors contributing to inequitable climate vulnerability. {9.3, 12.4, 13.4, 20.2, 31.4}

WORLD RESOURCES INSTITUTE

Action Report Finds Progress Lags on Every Measure Except EV Sales

November 14, 2023

Press Release

WASHINGTON (November 14, 2023) – Global efforts to limit warming to 1.5°C are failing across the board, with recent progress made on every indicator — except electric passenger car sales — lagging significantly behind the pace and scale that is necessary to address the climate crisis, according to the *State of Climate Action 2023* report.

Published under Systems Change Lab, the report is a joint effort of the Bezos Earth Fund, Climate Action Tracker (a project of Climate Analytics and NewClimate Institute), ClimateWorks Foundation, the United Nations Climate Change High-Level Champions and World Resources Institute (WRI).

The *State of Climate Action 2023* offers the world's most comprehensive roadmap of how to close the global gap in climate action across sectors and can inform governments' rapid response plan to the Global Stocktake at COP28.

"In a year where climate change has been wreaking havoc across the world, it's clear global efforts to curb emissions are falling short. Continued incremental change is not an option; 1.5°C is still achievable but we urgently need a step change in climate action. The *State of Climate Action* report outlines tangible sector-by-sector targets to orient governments in making that step change in line with the Paris Agreement's 1.5°C limit," said **Louise Jeffery** of NewClimate Institute and one of the report's lead authors.

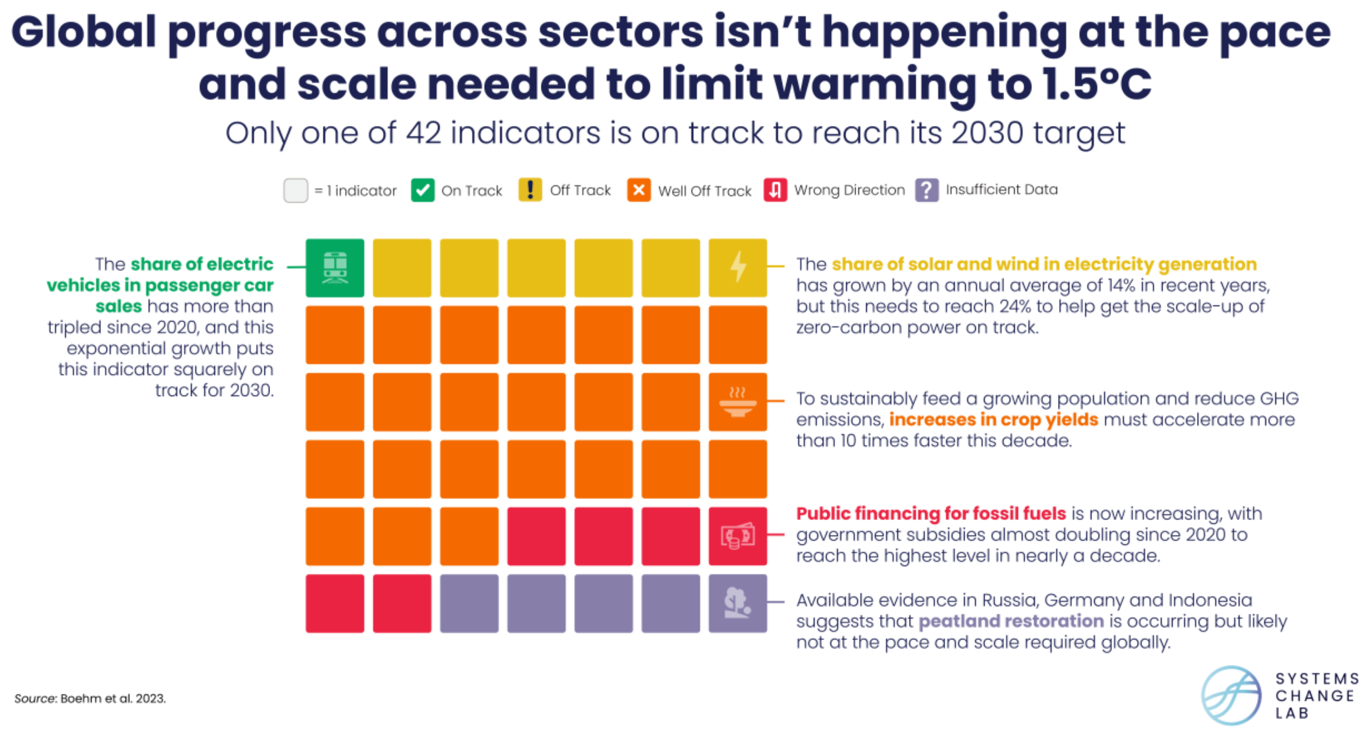
The report translates the Paris Agreement's temperature limit into 1.5°C-aligned targets for 2030 and 2050 to avoid intensifying climate impacts, while also minimizing harm to biodiversity and food security. These targets span sectors that account for roughly 85 percent of global GHG emissions — including power, buildings, industry, transport, forests and land, and food and agriculture — and also focus on the scale-up of carbon removal technologies and climate finance.

"Global efforts to limit warming to 1.5°C are lackluster at best. Despite decades of dire warnings and wake-up calls, our leaders have largely failed to mobilize climate action anywhere near the pace and scale needed," said **Sophie Boehm**, Research Associate II, World Resources Institute and lead author of the report. "Such delays leave us with very few routes to secure a livable future for all. There's no time left to tinker at the edges. Instead, we need immediate, transformational changes across every single sector this decade."

Across the 42 indicators assessed, only one — the share of electric vehicles in passenger car sales — is on track to reach its 2030 target. Of the other 41 indicators:

- **Six indicators are "off track," moving in the right direction at a promising but insufficient speed.**
- **24 indicators are "well off track," heading in the right direction but well below the required pace.**
- **Six indicators are headed in the wrong direction entirely, such that a U-turn in action is required.**
- **Five indicators have insufficient data to track progress.**

"It is only becoming more clear and more urgent to course-correct on climate," said **Ani Dasgupta**, President & CEO, World Resources Institute. "We already know what needs to be done, sector by sector, by 2030. The world has made some progress — in some cases, exponential progress — but overall, we are lagging, with several trends moving quickly in the wrong direction. It's going to take drastic action from all of us — governments, corporations, cities — to embrace the systemic change needed to create a livable and thriving future for people, nature and climate."



Achieving rapid transformations across all sectors to achieve global climate goals will require a tremendous acceleration in climate action this decade. For example, the analysis finds the world needs to:

> **Increase growth in solar and wind power.** The share of these two technologies in electricity generation has grown by an annual average of 14 percent in recent years, but this needs to reach 24 percent to get on track for 2030.
>
> **Phase out coal in electricity generation seven times faster than current rates.** This is equivalent to retiring roughly 240 average-sized coal-fired power plants each year through 2030. Though continued build-out of coal-fired power will increase the number of plants that need to be shuttered in the coming years.

Expand the coverage of rapid transit infrastructure six times faster. This is equivalent to constructing public transit systems roughly three times the size of New York City's network of subway rails, bus lanes and light-rail tracks each year throughout this decade.

The annual rate of deforestation — equivalent to deforesting 15 football (soccer) fields per minute in 2022 — **needs to be reduced four times faster over this decade.**

Shift to healthier, more sustainable diets eight times faster. This involves lowering per capita consumption of meat from cows, goats and sheep to approximately two servings per week or less across high-consuming regions (the Americas, Europe and Oceania) by 2030.

Worryingly, some indicators show a worsening trend in the most recent year of data. Efforts to end public financing for fossil fuels, dramatically reduce deforestation and expand carbon pricing systems experienced the most significant setbacks to progress in a single year, relative to recent trends.

Deforestation, for example, increased from 5.4 million hectares in 2021 to 5.8 million hectares in 2022, equivalent to permanently losing an area of forests greater than the size of Croatia in a single year. Similarly, government financing for fossil fuels increased sharply in 2021, with government subsidies, specifically, almost doubling from 2020 to reach the highest levels seen in nearly a decade. And due to data limitations for 2021, this is likely an underestimate.

"Something doesn't stack up. Clean energy markets are bullish; governments everywhere should be getting in on the act. Yet they continue to use public funds and subsidies to hold onto our fossil past. Meeting our climate goals means closing down coal power seven times faster and gas power more than ten times faster than today. It's absurd to keep investing in more of both. At COP28, governments should agree to a fair and fast phase out of fossil fuels," said **Claire Fyson**, one of the report's lead authors and Co-Head of Climate Analytics' policy team.

But amid this grim reality, some encouraging bright spots are emerging. For the first time in the *State of Climate Action* series, the share of electric vehicles in passenger car sales is on track, with these sales more than tripling since 2020.

"We're seeing electric vehicles take off faster than what we thought possible just a few years ago, in turn creating vast benefits for public health, the economy and the climate.

If we can replicate this progress in other areas, it shows that transformative change is possible if pursued in a concerted, emergency effort, moving them over positive tipping points," said **Helen Mountford**, President and CEO, ClimateWorks Foundation.

In other encouraging news, indicators focused on increasing mandatory corporate climate risk disclosure, sales of electric trucks and the share of EVs in the passenger car fleet saw the most significant gains in a single year, relative to recent trends. In 2022, for example, the number of countries with mandatory climate-related disclosures grew from 5 nations emitting 3% of global GHGs to 35 nations emitting 20% of global GHGs. New laws in the European Union and other high-emitting nations like India and Japan drove this annual increase.

"These findings on the *State of Climate Action* come at a pivotal moment," said **H.E. Razan Al Mubarak**, UN Climate Change High-Level Champion from the COP28 Presidency. "This year, as the first Global Stocktake under the Paris Agreement culminates at COP28, world leaders must recognize the insufficient progress to date and chart a path forward that builds on the successes we're seeing. This moment should serve as a springboard for accelerated actions."

The report will offer a guide for how decision-makers can allocate their limited time and resources to effectively tackle the climate crisis.

"This superb report provides compelling evidence of two seemingly irreconcilable truths," said Dr. **Andrew Steer**, President & CEO of the Bezos Earth Fund. "First, we are deep in a climate emergency and are critically off-track in reaching our 2030 goals. Second, we are seeing spectacular gains that are surprising even optimists. Progress is not linear but powerfully exponential. Hugely positive tipping points lie in our near-term future if we have the wisdom and courage to see them through. Today's negative headlines must prompt action, not paralysis. It's not too late! COP28 in December provides a chance for leaders to choose hope over despair."

How to cite this report: Published under Systems Change Lab, this report is a joint effort between the Bezos Earth Fund, Climate Action Tracker (a project of Climate Analytics and NewClimate Institute), ClimateWorks Foundation, the UN Climate Change High-Level Champions and World Resources Institute.

**Please do not attribute the State of Climate Action 2023 to a single organization.*

About Systems Change Lab

Systems Change Lab is a collaborative initiative that aims to spur action at the pace and scale needed to tackle some of the world's greatest challenges: limiting global warming to 1.5°C, halting biodiversity loss and building a just economy. Convened by World Resources Institute and the Bezos Earth Fund, Systems Change Lab supports the UN Climate Change High-Level Champions and works with key partners and funders including Climate Action Tracker (a project of Climate Analytics and NewClimate Institute), ClimateWorks Foundation, Global Environment Facility, Just Climate, Mission Possible Partnership, Systemiq, University of Exeter, and the University of Tokyo's Center for Global Commons, among others. Systems Change Lab is a component of the Global Commons Alliance.

About the Bezos Earth Fund

The Bezos Earth Fund is transforming the fight against climate change with the largest ever philanthropic commitment to climate and nature protection. We're investing $10 billion in this decisive decade to protect nature and drive systems-level change, creating a just transition to a low-carbon economy. By providing funding and expertise, we partner with organizations to accelerate innovation, break down barriers to success and create a more equitable and sustainable world. Join us in our mission to create a world where people prosper in harmony with nature.

About Climate Action Tracker

The Climate Action Tracker (CAT) is an independent research project that tracks government climate action and measures it against the globally agreed Paris Agreement goal of limiting warming to 1.5°C. A collaboration of two organizations, Climate Analytics and NewClimate Institute, the CAT has been providing this independent analysis to policymakers since 2009.

About Climate Analytics

Climate Analytics is a global climate science and policy institute engaged around the world in driving and supporting climate action aligned to the 1.5°C warming limit. It has offices in Africa, Australia and the Pacific, the Caribbean, North America and South Asia.

About NewClimate Institute

NewClimate Institute is a non-profit think tank supporting implementation of action against climate change in the context of sustainable development around the world. NewClimate Institute connects up-to-date research with real world decision-making processes with a focus on international climate negotiations, national and sectoral climate action and corporate climate commitments.

About ClimateWorks Foundation

ClimateWorks Foundation is a global platform for philanthropy to innovate and scale high-impact climate solutions that benefit people and the planet. We deliver global programs and services that equip philanthropy with the knowledge, networks, and solutions to drive climate progress for a more sustainable and equitable future. Since 2008, ClimateWorks has granted over $1.7 billion to more than 750 grantees in over 50 countries.

About the UN Climate Change High-Level Champions

The UN Climate Change High-Level Champions for COP27 and COP28 – Mahmoud Mohieldin and Razan Al Mubarak – drive real world momentum into the UN Climate Change negotiations. They do this by mobilizing climate action amongst non-State actors (companies, cities, regions, financial, educational and healthcare institutions) to achieve the goals of the Paris Agreement, in close collaboration with the UNFCCC, the Marrakech Partnership and the COP Presidencies.

About World Resources Institute

World Resources Institute (WRI) is a global research organization with offices in Brazil, China, Colombia, India, Indonesia, Mexico and the United States, and regional offices for Africa and Europe. Our over 1,700 staff work with partners to develop practical solutions that improve people's lives and ensure nature can thrive.

Media Contact:

Irene Berman-Vaporis

Head of Communications, Systems Change Lab and Climate Watch

Relevant Work

CLIMATE

RELEASE: Global Climate Report Card Finds Some Progress, but Action Across All Sectors Must Accelerate Dramatically to Limit Warming to 1.5 ℃

News OCTOBER 26, 2022

CLIMATE

RELEASE: Progress lagging across all sectors to limit warming to 1.5 C, but rapid change is possible, finds new report

News OCTOBER 28, 2021

ipcc

INTERGOVERNMENTAL PANEL ON climate change

CLIMATE CHANGE 2023
Synthesis Report

Summary for Policymakers

A Report of the Intergovernmental Panel on Climate Change

CLIMATE CHANGE 2023

Synthesis Report

Summary for Policymakers

Edited by

The Core Writing Team
Synthesis Report
IPCC

Hoesung Lee
Chairman
IPCC

José Romero
Head, Technical Support Unit
IPCC

Core Writing Team

Hoesung Lee (Chair), Katherine Calvin (USA), Dipak Dasgupta (India/USA), Gerhard Krinner (France/Germany), Aditi Mukherji (India), Peter Thorne (Ireland/United Kingdom), Christopher Trisos (South Africa), José Romero (Switzerland), Paulina Aldunce (Chile), Ko Barrett (USA), Gabriel Blanco (Argentina), William W. L. Cheung (Canada), Sarah L. Connors (France/United Kingdom), Fatima Denton (The Gambia), Aïda Diongue-Niang (Senegal), David Dodman (Jamaica/United Kingdom/Netherlands), Matthias Garschagen (Germany), Oliver Geden (Germany), Bronwyn Hayward (New Zealand), Christopher Jones (United Kingdom), Frank Jotzo (Australia), Thelma Krug (Brazil), Rodel Lasco (Philippines), June-Yi Lee (Republic of Korea), Valérie Masson-Delmotte (France), Malte Meinshausen (Australia/Germany), Katja Mintenbeck (Germany), Abdalah Mokssit (Morocco), Friederike E. L. Otto (United Kingdom/Germany), Minal Pathak (India), Anna Pirani (Italy), Elvira Poloczanska (United Kingdom/Australia), Hans-Otto Pörtner (Germany), Aromar Revi (India), Debra C. Roberts (South Africa), Joyashree Roy (India/Thailand), Alex C. Ruane (USA), Jim Skea (United Kingdom), Priyadarshi R. Shukla (India), Raphael Slade (United Kingdom), Aimée Slangen (The Netherlands), Youba Sokona (Mali), Anna A. Sörensson (Argentina), Melinda Tignor (USA/Germany), Detlef van Vuuren (The Netherlands), Yi-Ming Wei (China), Harald Winkler (South Africa), Panmao Zhai (China), Zinta Zommers (Latvia)

Technical Support Unit for the Synthesis Report

José Romero (Switzerland), Jinmi Kim (Republic of Korea), Erik F. Haites (Canada), Yonghun Jung (Republic of Korea), Robert Stavins (USA), Arlene Birt (USA), Meeyoung Ha (Republic of Korea), Dan Jezreel A. Orendain (Philippines), Lance Ignon (USA), Semin Park (Republic of Korea), Youngin Park (Republic of Korea)

Referencing this report:

IPCC, 2023: Summary for Policymakers. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001

Extended Writing Team

Jean-Charles Hourcade (France), Francis X. Johnson (Thailand/Sweden), Shonali Pachauri (Austria/India), Nicholas P. Simpson (South Africa/Zimbabwe), Chandni Singh (India), Adelle Thomas (Bahamas), Edmond Totin (Benin)

Review Editors

Paola Arias (Colombia), Mercedes Bustamante (Brazil), Ismail Elgizouli (Sudan), Gregory Flato (Canada), Mark Howden (Australia), Carlos Méndez (Venezuela), Joy Jacqueline Pereira (Malaysia), Ramón Pichs-Madruga (Cuba), Steven K Rose (USA), Yamina Saheb (Algeria/France), Roberto Sánchez Rodríguez (Mexico), Diana Ürge-Vorsatz (Hungary), Cunde Xiao (China), Noureddine Yassaa (Algeria)

Contributing Authors

Andrés Alegría (Germany/Honduras), Kyle Armour (USA), Birgit Bednar-Friedl (Austria), Kornelis Blok (The Netherlands), Guéladio Cissé (Switzerland/Mauritania/France), Frank Dentener (EU/Netherlands), Siri Eriksen (Norway), Erich Fischer (Switzerland), Gregory Garner (USA), Céline Guivarch (France), Marjolijn Haasnoot (The Netherlands), Gerrit Hansen (Germany), Mathias Hauser (Switzerland), Ed Hawkins (UK), Tim Hermans (The Netherlands), Robert Kopp (USA), Noëmie Leprince-Ringuet (France), Jared Lewis (Australia/New Zealand), Debora Ley (Mexico/Guatemala), Chloé Ludden (Germany/France), Leila Niamir (Iran/The Netherlands/Austria), Zebedee Nicholls (Australia), Shreya Some (India/Thailand), Sophie Szopa (France), Blair Trewin (Australia), Kaj-Ivar van der Wijst (The Netherlands), Gundula Winter (The Netherlands/Germany), Maximilian Witting (Germany)

Scientific Steering Committee

Hoesung Lee (Chair, IPCC), Amjad Abdulla (Maldives), Edvin Aldrian (Indonesia), Ko Barrett (United States of America), Eduardo Calvo (Peru), Carlo Carraro (Italy), Diriba Korecha Dadi (Ethiopia), Fatima Driouech (Morocco), Andreas Fischlin (Switzerland), Jan Fuglestvedt (Norway), Thelma Krug (Brazil), Nagmeldin G.E. Mahmoud (Sudan), Valérie Masson-Delmotte (France), Carlos Méndez (Venezuela), Joy Jacqueline Pereira (Malaysia), Ramón Pichs-Madruga (Cuba), Hans-Otto Pörtner (Germany), Andy Reisinger (New Zealand), Debra C. Roberts (South Africa), Sergey Semenov (Russian Federation), Priyadarshi Shukla (India), Jim Skea (United Kingdom), Youba Sokona (Mali), Kiyoto Tanabe (Japan), Muhammad Irfan Tariq (Pakistan), Diana Ürge-Vorsatz (Hungary), Carolina Vera (Argentina), Pius Yanda (United Republic of Tanzania), Noureddine Yassaa (Algeria), Taha M. Zatari (Saudi Arabia), Panmao Zhai (China)

Visual Conception and Information Design

Arlene Birt (USA), Meeyoung Ha (Republic of Korea)

Cover: Designed by Meeyoung Ha, IPCC SYR TSU

Photo Reference

"Fog opening the dawn" by Chung Jin Sil

The Weather and Climate Photography & Video Contest 2021, Korea Meteorological Administration
http://www.kma.go.kr/kma © KMA

THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

Editorial correspondence and requests to publish, reproduce or translate articles in part or in whole should be addressed to: IPCC c/o World Meteorological Organization (WMO) 7bis, avenue de la Paix Tel.: +41 22 730 8208 P.O. Box 2300 Fax: +41 22 730 8025 CH 1211 Geneva 2, Switzerland E-mail: IPCC-Sec@wmo.int www.ipcc.ch

Sources cited in this Synthesis Report

References for material contained in this report are given in curly brackets {} at the end of each paragraph.

In the Summary for Policymakers, the references refer to the numbers of the sections, figures, tables and boxes in the underlying Introduction and Topics of this Synthesis Report.

In the Introduction and Sections of the longer report, the references refer to the contributions of the Working Groups I, II and III (WGI, WGII, WGIII) to the Sixth Assessment Report and other IPCC Reports (in italicized curly brackets), or to other sections of the Synthesis Report itself (in round brackets).

The following abbreviations have been used:
SPM: Summary for Policymakers
TS: Technical Summary
ES: Executive Summary of a chapter
Numbers denote specific chapters and sections of a report.

Other IPCC reports cited in this Synthesis Report:
SR1.5: Global Warming of 1.5°C
SRCCL: Climate Change and Land
SROCC: The Ocean and Cryosphere in a Changing Climate

Summary for Policymakers

This Summary for Policymakers should be cited as:
IPCC, 2023: Summary for Policymakers. In: *Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001

Introduction

This Synthesis Report (SYR) of the IPCC Sixth Assessment Report (AR6) summarises the state of knowledge of climate change, its widespread impacts and risks, and climate change mitigation and adaptation. It integrates the main findings of the Sixth Assessment Report (AR6) based on contributions from the three Working Groups[1], and the three Special Reports[2]. The summary for Policymakers (SPM) is structured in three parts: SPM.A Current Status and Trends, SPM.B Future Climate Change, Risks, and Long-Term Responses, and SPM.C Responses in the Near Term[3].

This report recognizes the interdependence of climate, ecosystems and biodiversity, and human societies; the value of diverse forms of knowledge; and the close linkages between climate change adaptation, mitigation, ecosystem health, human well-being and sustainable development, and reflects the increasing diversity of actors involved in climate action.

Based on scientific understanding, key findings can be formulated as statements of fact or associated with an assessed level of confidence using the IPCC calibrated language[4].

---

1 The three Working Group contributions to AR6 are: AR6 Climate Change 2021: The Physical Science Basis; AR6 Climate Change 2022: Impacts, Adaptation and Vulnerability; and AR6 Climate Change 2022: Mitigation of Climate Change. Their assessments cover scientific literature accepted for publication respectively by 31 January 2021, 1 September 2021 and 11 October 2021.

2 The three Special Reports are: Global Warming of 1.5°C (2018): an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (SR1.5); Climate Change and Land (2019): an IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL); and The Ocean and Cryosphere in a Changing Climate (2019) (SROCC). The Special Reports cover scientific literature accepted for publication respectively by 15 May 2018, 7 April 2019 and 15 May 2019.

3 In this report, the near term is defined as the period until 2040. The long term is defined as the period beyond 2040.

4 Each finding is grounded in an evaluation of underlying evidence and agreement. The IPCC calibrated language uses five qualifiers to express a level of confidence: very low, low, medium, high and very high, and typeset in italics, for example, *medium confidence*. The following terms are used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, more likely than not >50–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms (extremely likely 95–100%; and extremely unlikely 0–5%) are also used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*. This is consistent with AR5 and the other AR6 Reports.

A. Current Status and Trends

Observed Warming and its Causes

A.1 Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850-1900 in 2011-2020. Global greenhouse gas emissions have continued to increase, with unequal historical and ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between and within countries, and among individuals (*high confidence*). {*2.1, Figure 2.1, Figure 2.2*}

A.1.1 Global surface temperature was 1.09 [0.95 to 1.20]°C[5] higher in 2011–2020 than 1850–1900[6], with larger increases over land (1.59 [1.34 to 1.83]°C) than over the ocean (0.88 [0.68 to 1.01]°C). Global surface temperature in the first two decades of the 21st century (2001–2020) was 0.99 [0.84 to 1.10]°C higher than 1850–1900. Global surface temperature has increased faster since 1970 than in any other 50-year period over at least the last 2000 years (*high confidence*). {*2.1.1, Figure 2.1*}

A.1.2 The *likely* range of total human-caused global surface temperature increase from 1850–1900 to 2010–2019[7] is 0.8°C to 1.3°C, with a best estimate of 1.07°C. Over this period, it is *likely* that well-mixed greenhouse gases (GHGs) contributed a warming of 1.0°C to 2.0°C[8], and other human drivers (principally aerosols) contributed a cooling of 0.0°C to 0.8°C, natural (solar and volcanic) drivers changed global surface temperature by –0.1°C to +0.1°C, and internal variability changed it by –0.2°C to +0.2°C. {*2.1.1, Figure 2.1*}

A.1.3 Observed increases in well-mixed GHG concentrations since around 1750 are unequivocally caused by GHG emissions from human activities over this period. Historical cumulative net CO_2 emissions from 1850 to 2019 were 2400 ± 240 $GtCO_2$ of which more than half (58%) occurred between 1850 and 1989, and about 42% occurred between 1990 and 2019 (*high confidence*). In 2019, atmospheric CO_2 concentrations (410 parts per million) were higher than at any time in at least 2 million years (*high confidence*), and concentrations of methane (1866 parts per billion) and nitrous oxide (332 parts per billion) were higher than at any time in at least 800,000 years (*very high confidence*). {*2.1.1, Figure 2.1*}

A.1.4 Global net anthropogenic GHG emissions have been estimated to be 59 ± 6.6 $GtCO_2$-eq[9] in 2019, about 12% (6.5 $GtCO_2$-eq) higher than in 2010 and 54% (21 $GtCO_2$-eq) higher than in 1990, with the largest share and growth in gross GHG emissions occurring in CO_2 from fossil fuels combustion and industrial processes (CO_2-FFI) followed by methane, whereas the highest relative growth occurred in fluorinated gases (F-gases), starting from low levels in 1990. Average annual GHG emissions during 2010–2019 were higher than in any previous decade on record, while the rate of growth between 2010 and 2019 (1.3% yr^{-1}) was lower than that between 2000 and 2009 (2.1% yr^{-1}). In 2019, approximately 79% of global GHG

---

5 Ranges given throughout the SPM represent *very likely* ranges (5–95% range) unless otherwise stated.

6 The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (0.19 [0.16 to 0.22] °C). Additionally, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have also increased the estimate of global surface temperature change by approximately 0.1°C, but this increase does not represent additional physical warming since AR5.

7 The period distinction with A.1.1 arises because the attribution studies consider this slightly earlier period. The observed warming to 2010–2019 is 1.06 [0.88 to 1.21]°C.

8 Contributions from emissions to the 2010–2019 warming relative to 1850–1900 assessed from radiative forcing studies are: CO_2 0.8 [0.5 to 1.2]°C; methane 0.5 [0.3 to 0.8]°C; nitrous oxide 0.1 [0.0 to 0.2]°C and fluorinated gases 0.1 [0.0 to 0.2]°C. {*2.1.1*}

9 GHG emission metrics are used to express emissions of different greenhouse gases in a common unit. Aggregated GHG emissions in this report are stated in CO_2-equivalents (CO_2-eq) using the Global Warming Potential with a time horizon of 100 years (GWP100) with values based on the contribution of Working Group I to the AR6. The AR6 WGI and WGIII reports contain updated emission metric values, evaluations of different metrics with regard to mitigation objectives, and assess new approaches to aggregating gases. The choice of metric depends on the purpose of the analysis and all GHG emission metrics have limitations and uncertainties, given that they simplify the complexity of the physical climate system and its response to past and future GHG emissions. {*2.1.1*}

emissions came from the sectors of energy, industry, transport, and buildings together and 22%[10] from agriculture, forestry and other land use (AFOLU). Emissions reductions in CO_2-FFI due to improvements in energy intensity of GDP and carbon intensity of energy, have been less than emissions increases from rising global activity levels in industry, energy supply, transport, agriculture and buildings. (*high confidence*) {*2.1.1*}

A.1.5 Historical contributions of CO_2 emissions vary substantially across regions in terms of total magnitude, but also in terms of contributions to CO_2-FFI and net CO_2 emissions from land use, land-use change and forestry (CO_2-LULUCF). In 2019, around 35% of the global population live in countries emitting more than 9 tCO_2-eq per capita[11] (excluding CO_2-LULUCF) while 41% live in countries emitting less than 3 tCO_2-eq per capita; of the latter a substantial share lacks access to modern energy services. Least Developed Countries (LDCs) and Small Island Developing States (SIDS) have much lower per capita emissions (1.7 tCO_2-eq and 4.6 tCO_2-eq, respectively) than the global average (6.9 tCO_2-eq), excluding CO_2-LULUCF. The 10% of households with the highest per capita emissions contribute 34–45% of global consumption-based household GHG emissions, while the bottom 50% contribute 13–15%. (*high confidence*) {*2.1.1, Figure 2.2*}

Observed Changes and Impacts

A.2 Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred. Human-caused climate change is already affecting many weather and climate extremes in every region across the globe. This has led to widespread adverse impacts and related losses and damages to nature and people (*high confidence*). Vulnerable communities who have historically contributed the least to current climate change are disproportionately affected (*high confidence*). {*2.1, Table 2.1, Figure 2.2, Figure 2.3*} (*Figure SPM.1*)

A.2.1 It is unequivocal that human influence has warmed the atmosphere, ocean and land. Global mean sea level increased by 0.20 [0.15 to 0.25] m between 1901 and 2018. The average rate of sea level rise was 1.3 [0.6 to 2.1] mm yr^{-1} between 1901 and 1971, increasing to 1.9 [0.8 to 2.9] mm yr^{-1} between 1971 and 2006, and further increasing to 3.7 [3.2 to 4.2] mm yr^{-1} between 2006 and 2018 (*high confidence*). Human influence was *very likely* the main driver of these increases since at least 1971. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has further strengthened since AR5. Human influence has *likely* increased the chance of compound extreme events since the 1950s, including increases in the frequency of concurrent heatwaves and droughts (*high confidence*). {*2.1.2, Table 2.1, Figure 2.3, Figure 3.4*} (*Figure SPM.1*)

A.2.2 Approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change. Human and ecosystem vulnerability are interdependent. Regions and people with considerable development constraints have high vulnerability to climatic hazards. Increasing weather and climate extreme events have exposed millions of people to acute food insecurity[12] and reduced water security, with the largest adverse impacts observed in many locations and/or communities in Africa, Asia, Central and South America, LDCs, Small Islands and the Arctic, and globally for Indigenous Peoples, small-scale food producers and low-income households. Between 2010 and 2020, human mortality from floods, droughts and storms was 15 times higher in highly vulnerable regions, compared to regions with very low vulnerability. (*high confidence*) {*2.1.2, 4.4*} (*Figure SPM.1*)

A.2.3 Climate change has caused substantial damages, and increasingly irreversible losses, in terrestrial, freshwater, cryospheric, and coastal and open ocean ecosystems (*high confidence*). Hundreds of local losses of species have been driven by increases in the magnitude of heat extremes (*high confidence*) with mass mortality events recorded on land and in the ocean (*very high confidence*). Impacts on some ecosystems are approaching irreversibility such as the impacts of hydrological changes resulting from the retreat of glaciers, or the changes in some mountain (*medium confidence*) and Arctic ecosystems driven by permafrost thaw (*high confidence*). {*2.1.2, Figure 2.3*} (*Figure SPM.1*)

---

10 GHG emission levels are rounded to two significant digits; as a consequence, small differences in sums due to rounding may occur. {*2.1.1*}

11 Territorial emissions.

12 Acute food insecurity can occur at any time with a severity that threatens lives, livelihoods or both, regardless of the causes, context or duration, as a result of shocks risking determinants of food security and nutrition, and is used to assess the need for humanitarian action. {*2.1*}

A.2.4 Climate change has reduced food security and affected water security, hindering efforts to meet Sustainable Development Goals (*high confidence*). Although overall agricultural productivity has increased, climate change has slowed this growth over the past 50 years globally (*medium confidence*), with related negative impacts mainly in mid- and low latitude regions but positive impacts in some high latitude regions (*high confidence*). Ocean warming and ocean acidification have adversely affected food production from fisheries and shellfish aquaculture in some oceanic regions *(high confidence)*. Roughly half of the world's population currently experience severe water scarcity for at least part of the year due to a combination of climatic and non-climatic drivers (*medium confidence*). {*2.1.2, Figure 2.3*} (*Figure SPM.1*)

A.2.5 In all regions increases in extreme heat events have resulted in human mortality and morbidity (*very high confidence*). The occurrence of climate-related food-borne and water-borne diseases (*very high confidence*) and the incidence of vector-borne diseases (*high confidence*) have increased. In assessed regions, some mental health challenges are associated with increasing temperatures (*high confidence*), trauma from extreme events (*very high confidence*), and loss of livelihoods and culture (*high confidence*). Climate and weather extremes are increasingly driving displacement in Africa, Asia, North America (*high confidence*), and Central and South America (*medium confidence*), with small island states in the Caribbean and South Pacific being disproportionately affected relative to their small population size (*high confidence*). {*2.1.2, Figure 2.3*} (*Figure SPM.1*)

A.2.6 Climate change has caused widespread adverse impacts and related losses and damages[13] to nature and people that are unequally distributed across systems, regions and sectors. Economic damages from climate change have been detected in climate-exposed sectors, such as agriculture, forestry, fishery, energy, and tourism. Individual livelihoods have been affected through, for example, destruction of homes and infrastructure, and loss of property and income, human health and food security, with adverse effects on gender and social equity. (*high confidence*) {*2.1.2*} (*Figure SPM.1*)

A.2.7 In urban areas, observed climate change has caused adverse impacts on human health, livelihoods and key infrastructure. Hot extremes have intensified in cities. Urban infrastructure, including transportation, water, sanitation and energy systems have been compromised by extreme and slow-onset events[14], with resulting economic losses, disruptions of services and negative impacts to well-being. Observed adverse impacts are concentrated amongst economically and socially marginalised urban residents. (*high confidence*) {*2.1.2*}

[13] In this report, the term 'losses and damages' refers to adverse observed impacts and/or projected risks and can be economic and/or non-economic (see Annex I: Glossary).

[14] Slow-onset events are described among the climatic-impact drivers of the AR6 WGI and refer to the risks and impacts associated with e.g., increasing temperature means, desertification, decreasing precipitation, loss of biodiversity, land and forest degradation, glacial retreat and related impacts, ocean acidification, sea level rise and salinization. {*2.1.2*}

Adverse impacts from human-caused climate change will continue to intensify

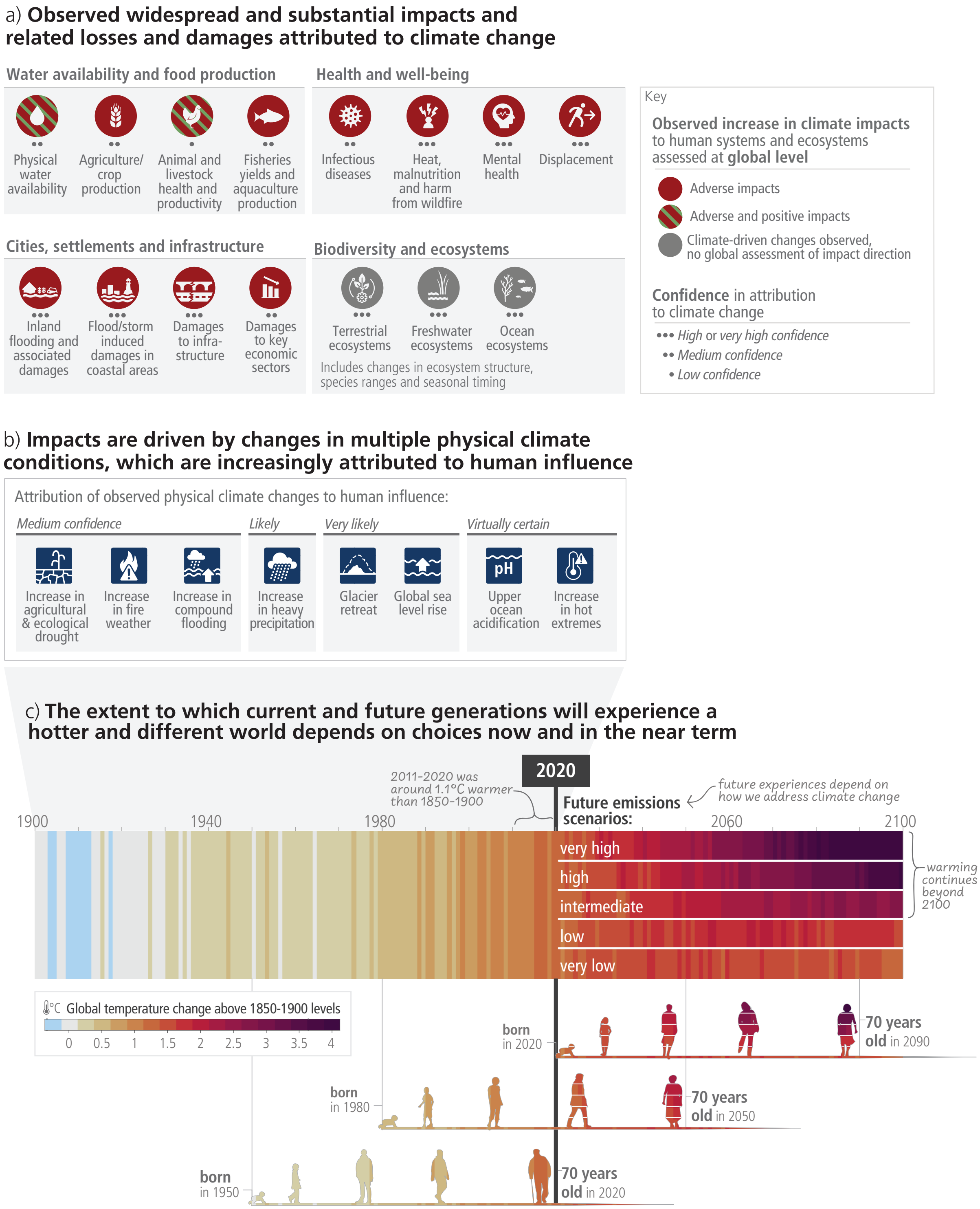


Figure SPM.1: **(a)** Climate change has already caused widespread impacts and related losses and damages on human systems and altered terrestrial, freshwater and ocean ecosystems worldwide. Physical water availability includes balance of water available from various sources including ground water, water quality and demand for water. Global mental health and displacement assessments reflect only assessed regions. Confidence levels reflect the assessment of attribution of the observed impact to climate change. **(b)** Observed impacts are connected to physical climate changes including many that have been attributed to human influence such as the selected climatic impact-drivers shown. Confidence and likelihood levels reflect the assessment of attribution of the observed climatic impact-driver to human influence. **(c)** Observed (1900–2020) and projected (2021–2100) changes in global surface temperature (relative to 1850-1900), which are linked to changes in climate conditions and impacts, illustrate how the climate has already changed and will change along the lifespan of three representative generations (born in 1950, 1980 and 2020). Future projections (2021–2100) of changes in global surface temperature are shown for very low (SSP1-1.9), low (SSP1-2.6), intermediate (SSP2-4.5), high (SSP3-7.0) and very high (SSP5-8.5) GHG emissions scenarios. Changes in annual global surface temperatures are presented as 'climate stripes', with future projections showing the human-caused long-term trends and continuing modulation by natural variability (represented here using observed levels of past natural variability). Colours on the generational icons correspond to the global surface temperature stripes for each year, with segments on future icons differentiating possible future experiences. {*2.1*, *2.1.2*, *Figure 2.1*, *Table 2.1*, *Figure 2.3*, *Cross-Section Box.2*, *3.1*, *Figure 3.3*, *4.1*, *4.3*} (*Box SPM.1*)

Current Progress in Adaptation and Gaps and Challenges

A.3 Adaptation planning and implementation has progressed across all sectors and regions, with documented benefits and varying effectiveness. Despite progress, adaptation gaps exist, and will continue to grow at current rates of implementation. Hard and soft limits to adaptation have been reached in some ecosystems and regions. Maladaptation is happening in some sectors and regions. Current global financial flows for adaptation are insufficient for, and constrain implementation of, adaptation options, especially in developing countries (*high confidence*). {*2.2, 2.3*}

A.3.1 Progress in adaptation planning and implementation has been observed across all sectors and regions, generating multiple benefits (*very high confidence*). Growing public and political awareness of climate impacts and risks has resulted in at least 170 countries and many cities including adaptation in their climate policies and planning processes (*high confidence*). {*2.2.3*}

A.3.2 Effectiveness[15] of adaptation in reducing climate risks[16] is documented for specific contexts, sectors and regions (*high confidence*). Examples of effective adaptation options include: cultivar improvements, on-farm water management and storage, soil moisture conservation, irrigation, agroforestry, community-based adaptation, farm and landscape level diversification in agriculture, sustainable land management approaches, use of agroecological principles and practices and other approaches that work with natural processes (*high confidence*). Ecosystem-based adaptation[17] approaches such as urban greening, restoration of wetlands and upstream forest ecosystems have been effective in reducing flood risks and urban heat (*high confidence*). Combinations of non-structural measures like early warning systems and structural measures like levees have reduced loss of lives in case of inland flooding (*medium confidence*). Adaptation options such as disaster risk management, early warning systems, climate services and social safety nets have broad applicability across multiple sectors (*high confidence*). {*2.2.3*}

A.3.3 Most observed adaptation responses are fragmented, incremental[18], sector-specific and unequally distributed across regions. Despite progress, adaptation gaps exist across sectors and regions, and will continue to grow under current levels of implementation, with the largest adaptation gaps among lower income groups. (*high confidence*) {*2.3.2*}

A.3.4 There is increased evidence of maladaptation in various sectors and regions. Maladaptation especially affects marginalised and vulnerable groups adversely. (*high confidence*) {*2.3.2*}

A.3.5 Soft limits to adaptation are currently being experienced by small-scale farmers and households along some low-lying coastal areas (*medium confidence*) resulting from financial, governance, institutional and policy constraints (*high confidence*). Some tropical, coastal, polar and mountain ecosystems have reached hard adaptation limits (*high confidence*). Adaptation does not prevent all losses and damages, even with effective adaptation and before reaching soft and hard limits (*high confidence*). {*2.3.2*}

---

15 Effectiveness refers here to the extent to which an adaptation option is anticipated or observed to reduce climate-related risk. {*2.2.3*}

16 See Annex I: Glossary. {*2.2.3*}

17 Ecosystem-based Adaptation (EbA) is recognized internationally under the Convention on Biological Diversity (CBD14/5). A related concept is Nature-based Solutions (NbS), see Annex I: Glossary.

18 Incremental adaptations to change in climate are understood as extensions of actions and behaviours that already reduce the losses or enhance the benefits of natural variations in extreme weather/climate events. {*2.3.2*}

A.3.6 Key barriers to adaptation are limited resources, lack of private sector and citizen engagement, insufficient mobilization of finance (including for research), low climate literacy, lack of political commitment, limited research and/or slow and low uptake of adaptation science, and low sense of urgency. There are widening disparities between the estimated costs of adaptation and the finance allocated to adaptation (*high confidence*). Adaptation finance has come predominantly from public sources, and a small proportion of global tracked climate finance was targeted to adaptation and an overwhelming majority to mitigation (*very high confidence*). Although global tracked climate finance has shown an upward trend since AR5, current global financial flows for adaptation, including from public and private finance sources, are insufficient and constrain implementation of adaptation options, especially in developing countries (*high confidence*). Adverse climate impacts can reduce the availability of financial resources by incurring losses and damages and through impeding national economic growth, thereby further increasing financial constraints for adaptation, particularly for developing and least developed countries (*medium confidence*). {*2.3.2*, *2.3.3*}

Box SPM.1 The use of scenarios and modelled pathways in the AR6 Synthesis Report

Modelled scenarios and pathways[19] are used to explore future emissions, climate change, related impacts and risks, and possible mitigation and adaptation strategies and are based on a range of assumptions, including socio-economic variables and mitigation options. These are quantitative projections and are neither predictions nor forecasts. Global modelled emission pathways, including those based on cost effective approaches contain regionally differentiated assumptions and outcomes, and have to be assessed with the careful recognition of these assumptions. Most do not make explicit assumptions about global equity, environmental justice or intra-regional income distribution. IPCC is neutral with regard to the assumptions underlying the scenarios in the literature assessed in this report, which do not cover all possible futures.[20] {*Cross-Section Box.2*}

WGI assessed the climate response to five illustrative scenarios based on Shared Socio-economic Pathways (SSPs)[21] that cover the range of possible future development of anthropogenic drivers of climate change found in the literature. High and very high GHG emissions scenarios (SSP3-7.0 and SSP5-8.5[22]) have CO_2 emissions that roughly double from current levels by 2100 and 2050, respectively. The intermediate GHG emissions scenario (SSP2-4.5) has CO_2 emissions remaining around current levels until the middle of the century. The very low and low GHG emissions scenarios (SSP1-1.9 and SSP1-2.6) have CO_2 emissions declining to net zero around 2050 and 2070, respectively, followed by varying levels of net negative CO_2 emissions. In addition, Representative Concentration Pathways (RCPs)[23] were used by WGI and WGII to assess regional climate changes, impacts and risks. In WGIII, a large number of global modelled emissions pathways were assessed, of which 1202 pathways were categorised based on their assessed global warming over the 21st century; categories range from pathways that limit warming to 1.5°C with more than 50% likelihood (noted >50% in this report) with no or limited overshoot (C1) to pathways that exceed 4°C (C8). {*Cross-Section Box.2*} (*Box SPM.1*, *Table 1*)

Global warming levels (GWLs) relative to 1850–1900 are used to integrate the assessment of climate change and related impacts and risks since patterns of changes for many variables at a given GWL are common to all scenarios considered and independent of timing when that level is reached. {*Cross-Section Box.2*}

---

19 In the literature, the terms pathways and scenarios are used interchangeably, with the former more frequently used in relation to climate goals. WGI primarily used the term scenarios and WGIII mostly used the term modelled emission and mitigation pathways. The SYR primarily uses scenarios when referring to WGI and modelled emission and mitigation pathways when referring to WGIII.

20 Around half of all modelled global emission pathways assume cost-effective approaches that rely on least-cost mitigation/abatement options globally. The other half looks at existing policies and regionally and sectorally differentiated actions.

21 SSP-based scenarios are referred to as SSPx-y, where 'SSPx' refers to the Shared Socioeconomic Pathway describing the socioeconomic trends underlying the scenarios, and 'y' refers to the level of radiative forcing (in watts per square metre, or $W m^{-2}$) resulting from the scenario in the year 2100. {*Cross-Section Box.2*}

22 Very high emissions scenarios have become *less likely* but cannot be ruled out. Warming levels >4°C may result from very high emissions scenarios, but can also occur from lower emission scenarios if climate sensitivity or carbon cycle feedbacks are higher than the best estimate. {*3.1.1*}

23 RCP-based scenarios are referred to as RCPy, where 'y' refers to the level of radiative forcing (in watts per square metre, or $W m^{-2}$) resulting from the scenario in the year 2100. The SSP scenarios cover a broader range of greenhouse gas and air pollutant futures than the RCPs. They are similar but not identical, with differences in concentration trajectories. The overall effective radiative forcing tends to be higher for the SSPs compared to the RCPs with the same label (*medium confidence*). {*Cross-Section Box.2*}

Box SPM.1, Table 1: Description and relationship of scenarios and modelled pathways considered across AR6 Working Group reports. {*Cross-Section Box.2 Figure 1*}

Category in WGIII	Category description	GHG emissions scenarios (SSPx-y*) in WGI & WGII	RCPy** in WGI & WGII
C1	limit warming to 1.5°C (>50%) with no or limited overshoot***	Very low (SSP1-1.9)	
C2	return warming to 1.5°C (>50%) after a high overshoot***		
C3	limit warming to 2°C (>67%)	Low (SSP1-2.6)	RCP2.6
C4	limit warming to 2°C (>50%)		
C5	limit warming to 2.5°C (>50%)		
C6	limit warming to 3°C (>50%)	Intermediate (SSP2-4.5)	RCP 4.5
C7	limit warming to 4°C (>50%)	High (SSP3-7.0)	
C8	exceed warming of 4°C (>50%)	Very high (SSP5-8.5)	RCP 8.5

* See footnote 21 for the SSPx-y terminology.

** See footnote 23 for the RCPy terminology.

*** Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C, high overshoot by 0.1°C-0.3°C, in both cases for up to several decades.

Current Mitigation Progress, Gaps and Challenges

A.4 Policies and laws addressing mitigation have consistently expanded since AR5. Global GHG emissions in 2030 implied by nationally determined contributions (NDCs) announced by October 2021 make it *likely* that warming will exceed 1.5°C during the 21st century and make it harder to limit warming below 2°C. There are gaps between projected emissions from implemented policies and those from NDCs and finance flows fall short of the levels needed to meet climate goals across all sectors and regions. (*high confidence*) {*2.2, 2.3, Figure 2.5, Table 2.2*}

A.4.1 The UNFCCC, Kyoto Protocol, and the Paris Agreement are supporting rising levels of national ambition. The Paris Agreement, adopted under the UNFCCC, with near universal participation, has led to policy development and target-setting at national and sub-national levels, in particular in relation to mitigation, as well as enhanced transparency of climate action and support (*medium confidence*). Many regulatory and economic instruments have already been deployed successfully (*high confidence*). In many countries, policies have enhanced energy efficiency, reduced rates of deforestation and accelerated technology deployment, leading to avoided and in some cases reduced or removed emissions (*high confidence*). Multiple lines of evidence suggest that mitigation policies have led to several[24] Gt CO_2-eq yr^{-1} of avoided global emissions (*medium confidence*). At least 18 countries have sustained absolute production-based GHG and consumption-based CO_2 reductions[25] for longer than 10 years. These reductions have only partly offset global emissions growth (*high confidence*). {*2.2.1, 2.2.2*}

A.4.2 Several mitigation options, notably solar energy, wind energy, electrification of urban systems, urban green infrastructure, energy efficiency, demand-side management, improved forest and crop/grassland management, and reduced food waste and loss, are technically viable, are becoming increasingly cost effective and are generally supported by the

[24] At least 1.8 $GtCO_2$-eq yr^{-1} can be accounted for by aggregating separate estimates for the effects of economic and regulatory instruments. Growing numbers of laws and executive orders have impacted global emissions and were estimated to result in 5.9 $GtCO_2$-eq yr^{-1} less emissions in 2016 than they otherwise would have been. (*medium confidence*) {*2.2.2*}

[25] Reductions were linked to energy supply decarbonisation, energy efficiency gains, and energy demand reduction, which resulted from both policies and changes in economic structure (*high confidence*). {*2.2.2*}

public. From 2010 to 2019 there have been sustained decreases in the unit costs of solar energy (85%), wind energy (55%), and lithium-ion batteries (85%), and large increases in their deployment, e.g., >10× for solar and >100× for electric vehicles (EVs), varying widely across regions. The mix of policy instruments that reduced costs and stimulated adoption includes public R&D, funding for demonstration and pilot projects, and demand-pull instruments such as deployment subsidies to attain scale. Maintaining emission-intensive systems may, in some regions and sectors, be more expensive than transitioning to low emission systems. (*high confidence*) {*2.2.2, Figure 2.4*}

A.4.3 A substantial 'emissions gap' exists between global GHG emissions in 2030 associated with the implementation of NDCs announced prior to COP26[26] and those associated with modelled mitigation pathways that limit warming to 1.5°C (>50%) with no or limited overshoot or limit warming to 2°C (>67%) assuming immediate action (*high confidence*). This would make it *likely* that warming will exceed 1.5°C during the 21st century (*high confidence*). Global modelled mitigation pathways that limit warming to 1.5°C (>50%) with no or limited overshoot or limit warming to 2°C (>67%) assuming immediate action imply deep global GHG emissions reductions this decade (*high confidence*) (see SPM Box 1, Table 1, B.6)[27]. Modelled pathways that are consistent with NDCs announced prior to COP26 until 2030 and assume no increase in ambition thereafter have higher emissions, leading to a median global warming of 2.8 [2.1 to 3.4] °C by 2100 (*medium confidence*). Many countries have signalled an intention to achieve net zero GHG or net zero CO_2 by around mid-century but pledges differ across countries in terms of scope and specificity, and limited policies are to date in place to deliver on them. {*2.3.1*, *Table 2.2*, *Figure 2.5*, *Table 3.1*, *4.1*}

A.4.4 Policy coverage is uneven across sectors (*high confidence*). Policies implemented by the end of 2020 are projected to result in higher global GHG emissions in 2030 than emissions implied by NDCs, indicating an 'implementation gap' (*high confidence*). Without a strengthening of policies, global warming of 3.2 [2.2 to 3.5] °C is projected by 2100 (*medium confidence*). {*2.2.2*, *2.3.1*, *3.1.1*, *Figure 2.5*} (*Box SPM.1*, *Figure SPM.5*)

A.4.5 The adoption of low-emission technologies lags in most developing countries, particularly least developed ones, due in part to limited finance, technology development and transfer, and capacity (*medium confidence*). The magnitude of climate finance flows has increased over the last decade and financing channels have broadened but growth has slowed since 2018 (*high confidence*). Financial flows have developed heterogeneously across regions and sectors (*high confidence*). Public and private finance flows for fossil fuels are still greater than those for climate adaptation and mitigation (*high confidence*). The overwhelming majority of tracked climate finance is directed towards mitigation, but nevertheless falls short of the levels needed to limit warming to below 2°C or to 1.5°C across all sectors and regions (see C7.2) (*very high confidence*). In 2018, public and publicly mobilised private climate finance flows from developed to developing countries were below the collective goal under the UNFCCC and Paris Agreement to mobilise USD 100 billion per year by 2020 in the context of meaningful mitigation action and transparency on implementation (*medium confidence*). {*2.2.2*, *2.3.1*, *2.3.3*}

---

[26] Due to the literature cutoff date of WGIII, the additional NDCs submitted after 11 October 2021 are not assessed here. {*Footnote 32 in the Longer Report*}

[27] Projected 2030 GHG emissions are 50 (47–55) $GtCO_2$-eq if all conditional NDC elements are taken into account. Without conditional elements, the global emissions are projected to be approximately similar to modelled 2019 levels at 53 (50–57) $GtCO_2$-eq. {*2.3.1*, *Table 2.2*}

B. Future Climate Change, Risks, and Long-Term Responses

Future Climate Change

B.1 Continued greenhouse gas emissions will lead to increasing global warming, with the best estimate of reaching 1.5°C in the near term in considered scenarios and modelled pathways. Every increment of global warming will intensify multiple and concurrent hazards (*high confidence*). Deep, rapid, and sustained reductions in greenhouse gas emissions would lead to a discernible slowdown in global warming within around two decades, and also to discernible changes in atmospheric composition within a few years (*high confidence*). {*Cross-Section Boxes 1 and 2, 3.1, 3.3, Table 3.1, Figure 3.1, 4.3*} (*Figure SPM.2, Box SPM.1*)

B.1.1 Global warming[28] will continue to increase in the near term (2021–2040) mainly due to increased cumulative CO_2 emissions in nearly all considered scenarios and modelled pathways. In the near term, global warming *is more likely than not* to reach 1.5°C even under the very low GHG emission scenario (SSP1-1.9) and *likely* or *very likely* to exceed 1.5°C under higher emissions scenarios. In the considered scenarios and modelled pathways, the best estimates of the time when the level of global warming of 1.5°C is reached lie in the near term[29]. Global warming declines back to below 1.5°C by the end of the 21st century in some scenarios and modelled pathways (see B.7). The assessed climate response to GHG emissions scenarios results in a best estimate of warming for 2081–2100 that spans a range from 1.4°C for a very low GHG emissions scenario (SSP1-1.9) to 2.7°C for an intermediate GHG emissions scenario (SSP2-4.5) and 4.4°C for a very high GHG emissions scenario (SSP5-8.5)[30], with narrower uncertainty ranges[31] than for corresponding scenarios in AR5. {*Cross-Section Boxes 1 and 2*, *3.1.1*, *3.3.4*, *Table 3.1*, *4.3*} (*Box SPM.1*)

B.1.2 Discernible differences in trends of global surface temperature between contrasting GHG emissions scenarios (SSP1-1.9 and SSP1-2.6 vs. SSP3-7.0 and SSP5-8.5) would begin to emerge from natural variability[32] within around 20 years. Under these contrasting scenarios, discernible effects would emerge within years for GHG concentrations, and sooner for air quality improvements, due to the combined targeted air pollution controls and strong and sustained methane emissions reductions. Targeted reductions of air pollutant emissions lead to more rapid improvements in air quality within years compared to reductions in GHG emissions only, but in the long term, further improvements are projected in scenarios that combine efforts to reduce air pollutants as well as GHG emissions[33]. (*high confidence*) {*3.1.1*} (*Box SPM.1*)

B.1.3 Continued emissions will further affect all major climate system components. With every additional increment of global warming, changes in extremes continue to become larger. Continued global warming is projected to further intensify the global water cycle, including its variability, global monsoon precipitation, and very wet and very dry weather and

---

28 Global warming (see Annex I: Glossary) is here reported as running 20-year averages, unless stated otherwise, relative to 1850–1900. Global surface temperature in any single year can vary above or below the long-term human-caused trend, due to natural variability. The internal variability of global surface temperature in a single year is estimated to be about ±0.25°C (5–95% range, *high confidence*). The occurrence of individual years with global surface temperature change above a certain level does not imply that this global warming level has been reached. {*4.3, Cross-Section Box.2*}

29 Median five-year interval at which a 1.5°C global warming level is reached (50% probability) in categories of modelled pathways considered in WGIII is 2030–2035. By 2030, global surface temperature in any individual year could exceed 1.5°C relative to 1850–1900 with a probability between 40% and 60%, across the five scenarios assessed in WGI (*medium confidence*). In all scenarios considered in WGI except the very high emissions scenario (SSP5-8.5), the midpoint of the first 20-year running average period during which the assessed average global surface temperature change reaches 1.5°C lies in the first half of the 2030s. In the very high GHG emissions scenario, the midpoint is in the late 2020s. {*3.1.1*, *3.3.1*, *4.3*} (*Box SPM.1*)

30 The best estimates [and *very likely* ranges] for the different scenarios are: 1.4 [1.0 to 1.8]°C (SSP1-1.9); 1.8 [1.3 to 2.4]°C (SSP1-2.6); 2.7 [2.1 to 3.5]°C (SSP2-4.5); 3.6 [2.8 to 4.6]°C (SSP3-7.0); and 4.4 [3.3 to 5.7]°C (SSP5-8.5). {*3.1.1*} (*Box SPM.1*)

31 Assessed future changes in global surface temperature have been constructed, for the first time, by combining multi-model projections with observational constraints and the assessed equilibrium climate sensitivity and transient climate response. The uncertainty range is narrower than in the AR5 thanks to improved knowledge of climate processes, paleoclimate evidence and model-based emergent constraints. {*3.1.1*}

32 See Annex I: Glossary. Natural variability includes natural drivers and internal variability. The main internal variability phenomena include El Niño-Southern Oscillation, Pacific Decadal Variability and Atlantic Multi-decadal Variability. {*4.3*}

33 Based on additional scenarios.

climate events and seasons (*high confidence*). In scenarios with increasing CO_2 emissions, natural land and ocean carbon sinks are projected to take up a decreasing proportion of these emissions (*high confidence*). Other projected changes include further reduced extents and/or volumes of almost all cryospheric elements[34] (*high confidence*), further global mean sea level rise (*virtually certain*), and increased ocean acidification (*virtually certain*) and deoxygenation (*high confidence*). {*3.1.1, 3.3.1, Figure 3.4*} (*Figure SPM.2*)

B.1.4 With further warming, every region is projected to increasingly experience concurrent and multiple changes in climatic impact-drivers. Compound heatwaves and droughts are projected to become more frequent, including concurrent events across multiple locations (*high confidence*). Due to relative sea level rise, current 1-in-100 year extreme sea level events are projected to occur at least annually in more than half of all tide gauge locations by 2100 under all considered scenarios (*high confidence*). Other projected regional changes include intensification of tropical cyclones and/or extratropical storms (*medium confidence*), and increases in aridity and fire weather (*medium* to *high confidence*). {*3.1.1, 3.1.3*}

B.1.5 Natural variability will continue to modulate human-caused climate changes, either attenuating or amplifying projected changes, with little effect on centennial-scale global warming (*high confidence*). These modulations are important to consider in adaptation planning, especially at the regional scale and in the near term. If a large explosive volcanic eruption were to occur[35], it would temporarily and partially mask human-caused climate change by reducing global surface temperature and precipitation for one to three years (*medium confidence*). {*4.3*}

34 Permafrost, seasonal snow cover, glaciers, the Greenland and Antarctic Ice Sheets, and Arctic sea ice.

35 Based on 2500-year reconstructions, eruptions with a radiative forcing more negative than -1 W m^{-2}, related to the radiative effect of volcanic stratospheric aerosols in the literature assessed in this report, occur on average twice per century. {*4.3*}

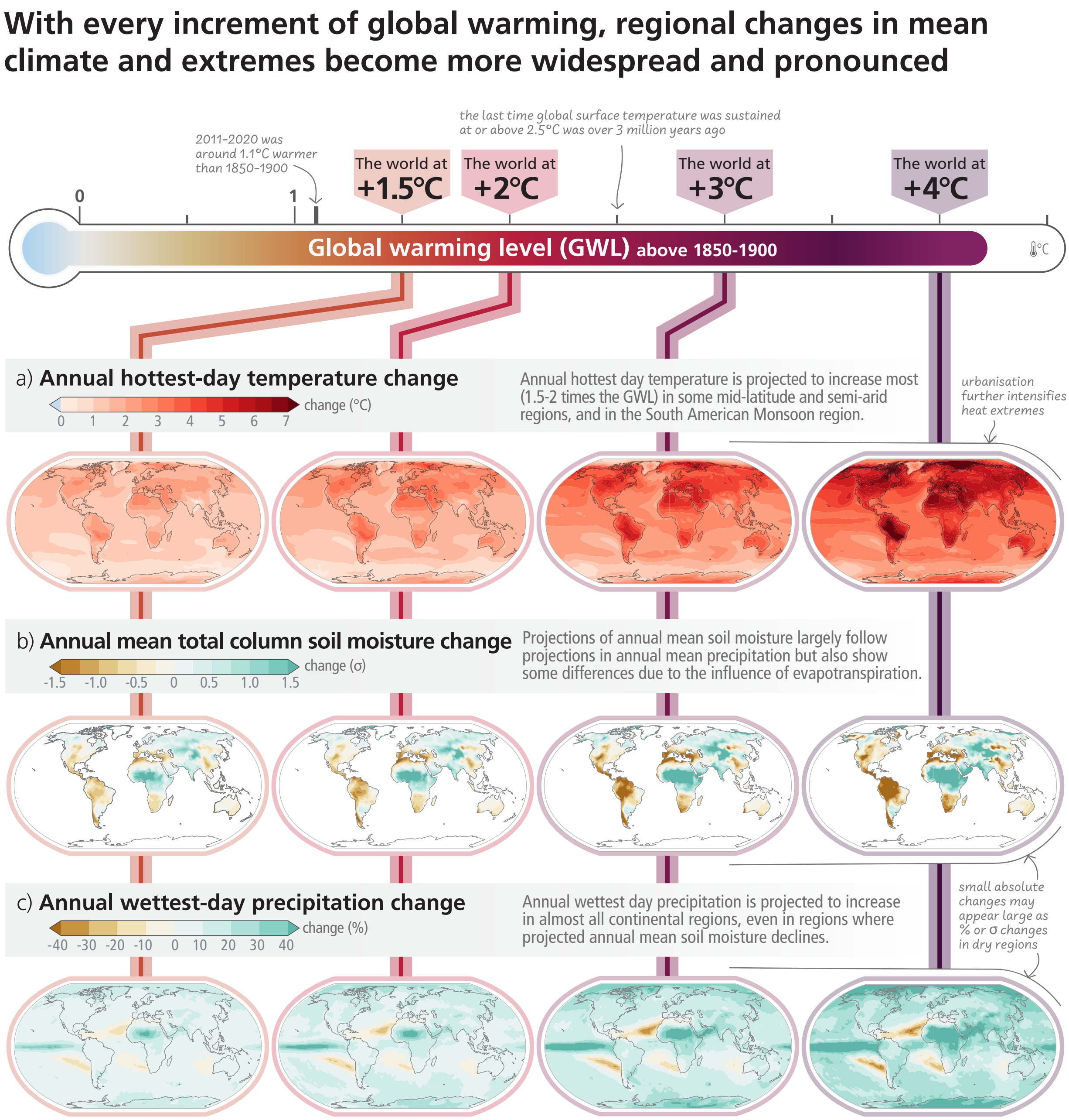


Figure SPM.2: Projected changes of annual maximum daily maximum temperature, annual mean total column soil moisture and annual maximum 1-day precipitation at global warming levels of 1.5°C, 2°C, 3°C, and 4°C relative to 1850–1900. Projected **(a)** annual maximum daily temperature change (°C), **(b)** annual mean total column soil moisture change (standard deviation), **(c)** annual maximum 1-day precipitation change (%). The panels show CMIP6 multi-model median changes. In panels (b) and (c), large positive relative changes in dry regions may correspond to small absolute changes. In panel (b), the unit is the standard deviation of interannual variability in soil moisture during 1850–1900. Standard deviation is a widely used metric in characterising drought severity. A projected reduction in mean soil moisture by one standard deviation corresponds to soil moisture conditions typical of droughts that occurred about once every six years during 1850–1900. The WGI Interactive Atlas (https://interactive-atlas.ipcc.ch/) can be used to explore additional changes in the climate system across the range of global warming levels presented in this figure. {*Figure 3.1, Cross-Section Box.2*}

Climate Change Impacts and Climate-Related Risks

B.2 For any given future warming level, many climate-related risks are higher than assessed in AR5, and projected long-term impacts are up to multiple times higher than currently observed (*high confidence*). Risks and projected adverse impacts and related losses and damages from climate change escalate with every increment of global warming (*very high confidence*). Climatic and non-climatic risks will increasingly interact, creating compound and cascading risks that are more complex and difficult to manage (*high confidence*). {*Cross-Section Box.2, 3.1, 4.3, Figure 3.3, Figure 4.3*} (*Figure SPM.3, Figure SPM.4*)

B.2.1 In the near term, every region in the world is projected to face further increases in climate hazards (*medium* to *high confidence*, depending on region and hazard), increasing multiple risks to ecosystems and humans (*very high confidence*). Hazards and associated risks expected in the near term include an increase in heat-related human mortality and morbidity (*high confidence*), food-borne, water-borne, and vector-borne diseases (*high confidence*), and mental health challenges[36] (*very high confidence*), flooding in coastal and other low-lying cities and regions (*high confidence*), biodiversity loss in land, freshwater and ocean ecosystems (*medium* to *very high confidence*, depending on ecosystem), and a decrease in food production in some regions (*high confidence*). Cryosphere-related changes in floods, landslides, and water availability have the potential to lead to severe consequences for people, infrastructure and the economy in most mountain regions (*high confidence*). The projected increase in frequency and intensity of heavy precipitation (*high confidence*) will increase rain-generated local flooding (*medium confidence*). {*Figure 3.2*, *Figure 3.3*, *4.3*, *Figure 4.3*} (*Figure SPM.3*, *Figure SPM.4*)

B.2.2 Risks and projected adverse impacts and related losses and damages from climate change will escalate with every increment of global warming (*very high confidence*). They are higher for global warming of 1.5°C than at present, and even higher at 2°C (*high confidence*). Compared to the AR5, global aggregated risk levels[37] (Reasons for Concern[38]) are assessed to become high to very high at lower levels of global warming due to recent evidence of observed impacts, improved process understanding, and new knowledge on exposure and vulnerability of human and natural systems, including limits to adaptation (*high confidence*). Due to unavoidable sea level rise (see also B.3), risks for coastal ecosystems, people and infrastructure will continue to increase beyond 2100 (*high confidence*). {*3.1.2*, *3.1.3*, *Figure 3.4*, *Figure 4.3*} (*Figure SPM.3*, *Figure SPM.4*)

B.2.3 With further warming, climate change risks will become increasingly complex and more difficult to manage. Multiple climatic and non-climatic risk drivers will interact, resulting in compounding overall risk and risks cascading across sectors and regions. Climate-driven food insecurity and supply instability, for example, are projected to increase with increasing global warming, interacting with non-climatic risk drivers such as competition for land between urban expansion and food production, pandemics and conflict. (*high confidence*) {*3.1.2*, *4.3*, *Figure 4.3*}

B.2.4 For any given warming level, the level of risk will also depend on trends in vulnerability and exposure of humans and ecosystems. Future exposure to climatic hazards is increasing globally due to socio-economic development trends including migration, growing inequality and urbanisation. Human vulnerability will concentrate in informal settlements and rapidly growing smaller settlements. In rural areas vulnerability will be heightened by high reliance on climate-sensitive livelihoods. Vulnerability of ecosystems will be strongly influenced by past, present, and future patterns of unsustainable consumption and production, increasing demographic pressures, and persistent unsustainable use and management of land, ocean, and water. Loss of ecosystems and their services has cascading and long-term impacts on people globally, especially for Indigenous Peoples and local communities who are directly dependent on ecosystems to meet basic needs. (*high confidence*) {*Cross-Section Box.2 Figure 1c*, *3.1.2*, *4.3*}

[36] In all assessed regions.

[37] Undetectable risk level indicates no associated impacts are detectable and attributable to climate change; moderate risk indicates associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks; high risk indicates severe and widespread impacts that are judged to be high on one or more criteria for assessing key risks; and very high risk level indicates very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks. {*3.1.2*}

[38] The Reasons for Concern (RFC) framework communicates scientific understanding about accrual of risk for five broad categories. RFC1: Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. RFC2: Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events. RFC3: Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. RFC4: Global aggregate impacts: impacts to socio-ecological systems that can be aggregated globally into a single metric. RFC5: Large-scale singular events: relatively large, abrupt and sometimes irreversible changes in systems caused by global warming. See also Annex I: Glossary. {*3.1.2, Cross-Section Box.2*}

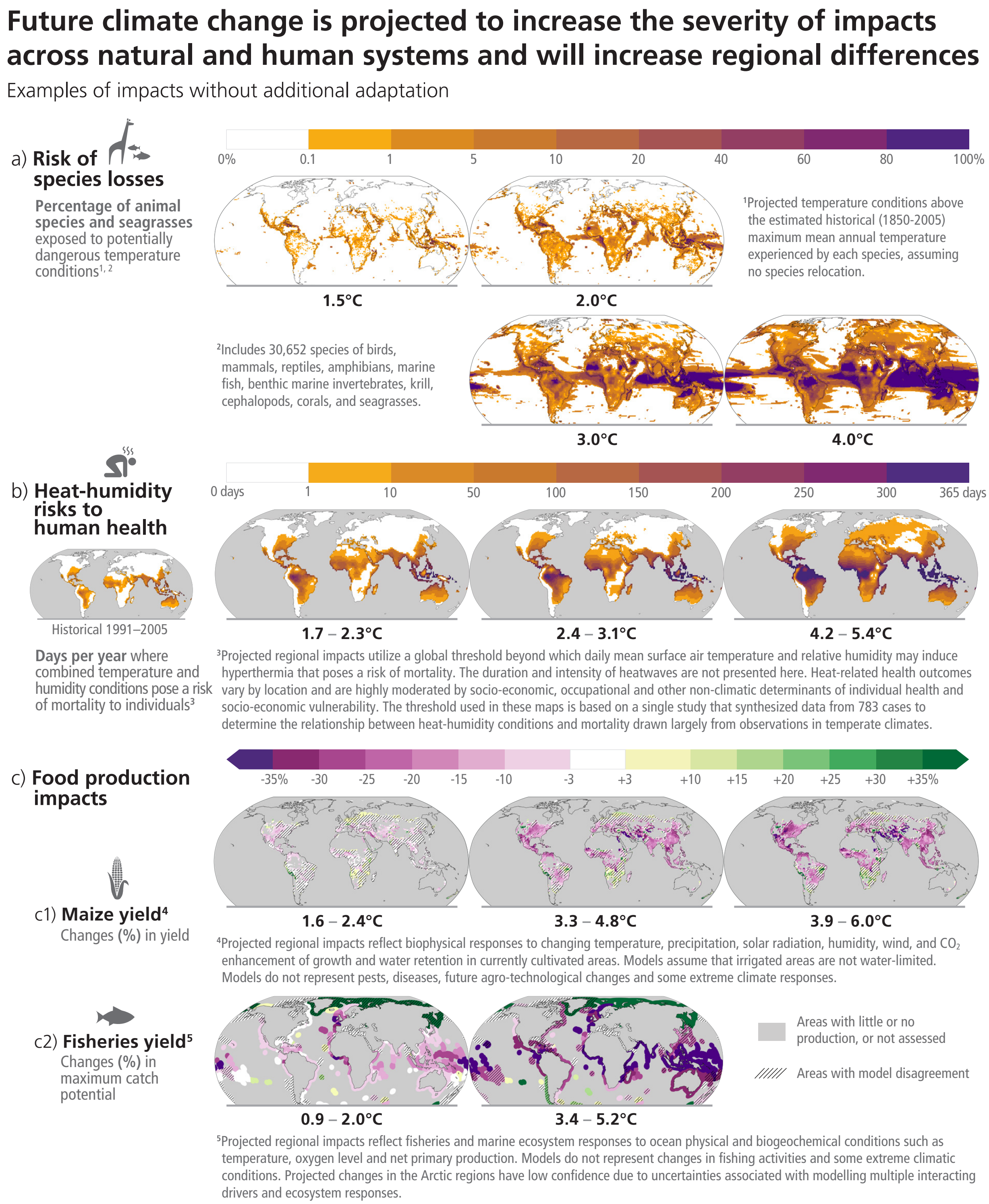


Figure SPM.3: Projected risks and impacts of climate change on natural and human systems at different global warming levels (GWLs) relative to 1850-1900 levels. Projected risks and impacts shown on the maps are based on outputs from different subsets of Earth system and impact models that were used to project each impact indicator without additional adaptation. WGII provides further assessment of the impacts on human and natural systems using these projections and additional lines of evidence. **(a)** Risks of species losses as indicated by the percentage of assessed species exposed to potentially dangerous temperature conditions, as defined by conditions beyond the estimated historical (1850–2005) maximum mean annual temperature experienced by each species, at GWLs of 1.5°C, 2°C, 3°C and 4°C. Underpinning projections of temperature are from 21 Earth system models and do not consider extreme events impacting ecosystems such as the Arctic. **(b)** Risks to human health as indicated by the days per year of population exposure to hyperthermic conditions that pose a risk of mortality from surface air temperature and humidity conditions for historical period (1991–2005) and at GWLs of 1.7°C–2.3°C (mean = 1.9°C; 13 climate models), 2.4°C–3.1°C (2.7°C; 16 climate models) and 4.2°C–5.4°C (4.7°C; 15 climate models). Interquartile ranges of GWLs by 2081–2100 under RCP2.6, RCP4.5 and RCP8.5. The presented index is consistent with common features found in many indices included within WGI and WGII assessments. **(c)** Impacts on food production: (c1) Changes in maize yield by 2080–2099 relative to 1986–2005 at projected GWLs of 1.6°C–2.4°C (2.0°C), 3.3°C–4.8°C (4.1°C) and 3.9°C–6.0°C (4.9°C). Median yield changes from an ensemble of 12 crop models, each driven by bias-adjusted outputs from 5 Earth system models, from the Agricultural Model Intercomparison and Improvement Project (AgMIP) and the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP). Maps depict

2080–2099 compared to 1986–2005 for current growing regions (>10 ha), with the corresponding range of future global warming levels shown under SSP1-2.6, SSP3-7.0 and SSP5-8.5, respectively. Hatching indicates areas where <70% of the climate-crop model combinations agree on the sign of impact. (c2) Change in maximum fisheries catch potential by 2081–2099 relative to 1986–2005 at projected GWLs of 0.9°C–2.0°C (1.5°C) and 3.4°C–5.2°C (4.3°C). GWLs by 2081–2100 under RCP2.6 and RCP8.5. Hatching indicates where the two climate-fisheries models disagree in the direction of change. Large relative changes in low yielding regions may correspond to small absolute changes. Biodiversity and fisheries in Antarctica were not analysed due to data limitations. Food security is also affected by crop and fishery failures not presented here. {*3.1.2, Figure 3.2, Cross-Section Box.2*} (*Box SPM.1*)

Risks are increasing with every increment of warming

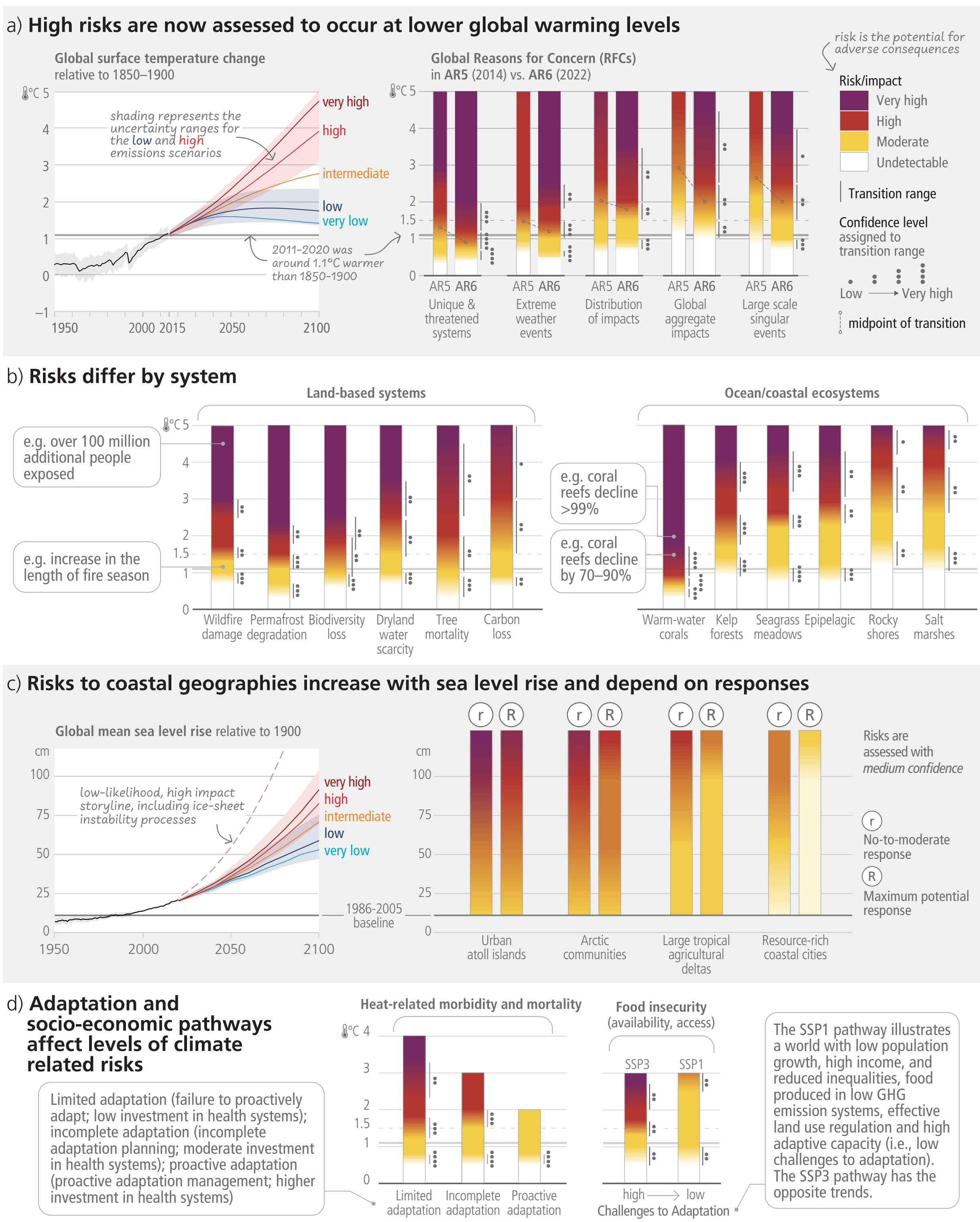


Figure SPM.4: Subset of assessed climate outcomes and associated global and regional climate risks. The burning embers result from a literature based expert elicitation. **Panel (a): Left** – Global surface temperature changes in °C relative to 1850–1900. These changes were obtained by combining CMIP6 model simulations with observational constraints based on past simulated warming, as well as an updated assessment of equilibrium climate sensitivity. *Very likely* ranges are shown for the low and high GHG emissions scenarios (SSP1-2.6 and SSP3-7.0) (Cross-Section Box.2). **Right** – Global Reasons for Concern (RFC), comparing AR6 (thick embers) and AR5 (thin embers) assessments. Risk transitions have generally shifted towards lower temperatures with updated scientific understanding. Diagrams are shown for each RFC, assuming low to no adaptation. Lines connect the midpoints of the transitions from moderate to high risk across AR5 and AR6. **Panel (b)**: Selected global risks for land and ocean ecosystems, illustrating general increase of risk with global warming levels with low to no adaptation. **Panel (c): Left** - Global mean sea level change in centimetres, relative to 1900. The historical changes (black) are observed by tide gauges before 1992 and altimeters afterwards. The future changes to 2100 (coloured lines and shading) are assessed consistently with observational constraints based on emulation of CMIP, ice-sheet, and glacier models, and *likely* ranges are shown for SSP1-2.6 and SSP3-7.0. **Right** - Assessment of the combined risk of coastal flooding, erosion and salinization for four illustrative coastal geographies in 2100, due to changing mean and extreme sea levels, under two response scenarios, with respect to the SROCC baseline period (1986–2005). The assessment does not account for changes in extreme sea level beyond those directly induced by mean sea level rise; risk levels could increase if other changes in extreme sea levels were considered (e.g., due to changes in cyclone intensity). "No-to-moderate response" describes efforts as of today (i.e., no further significant action or new types of actions). "Maximum potential response" represent a combination of responses implemented to their full extent and thus significant additional efforts compared to today, assuming minimal financial, social and political barriers. (In this context, 'today' refers to 2019.) The assessment criteria include exposure and vulnerability, coastal hazards, in-situ responses and planned relocation. Planned relocation refers to managed retreat or resettlements. The term response is used here instead of adaptation because some responses, such as retreat, may or may not be considered to be adaptation. **Panel (d)**: Selected risks under different socio-economic pathways, illustrating how development strategies and challenges to adaptation influence risk. **Left** - Heat-sensitive human health outcomes under three scenarios of adaptation effectiveness. The diagrams are truncated at the nearest whole ºC within the range of temperature change in 2100 under three SSP scenarios. **Right** - Risks associated with food security due to climate change and patterns of socio-economic development. Risks to food security include availability and access to food, including population at risk of hunger, food price increases and increases in disability adjusted life years attributable to childhood underweight. Risks are assessed for two contrasted socio-economic pathways (SSP1 and SSP3) excluding the effects of targeted mitigation and adaptation policies. {*Figure 3.3*} (*Box SPM.1*)

Likelihood and Risks of Unavoidable, Irreversible or Abrupt Changes

B.3 Some future changes are unavoidable and/or irreversible but can be limited by deep, rapid, and sustained global greenhouse gas emissions reduction. The likelihood of abrupt and/or irreversible changes increases with higher global warming levels. Similarly, the probability of low-likelihood outcomes associated with potentially very large adverse impacts increases with higher global warming levels. (*high confidence*) {*3.1*}

B.3.1 Limiting global surface temperature does not prevent continued changes in climate system components that have multi-decadal or longer timescales of response (*high confidence*). Sea level rise is unavoidable for centuries to millennia due to continuing deep ocean warming and ice sheet melt, and sea levels will remain elevated for thousands of years (*high confidence*). However, deep, rapid, and sustained GHG emissions reductions would limit further sea level rise acceleration and projected long-term sea level rise commitment. Relative to 1995–2014, the *likely* global mean sea level rise under the SSP1-1.9 GHG emissions scenario is 0.15–0.23 m by 2050 and 0.28–0.55 m by 2100; while for the SSP5-8.5 GHG emissions scenario it is 0.20–0.29 m by 2050 and 0.63–1.01 m by 2100 (*medium confidence*). Over the next 2000 years, global mean sea level will rise by about 2–3 m if warming is limited to 1.5°C and 2–6 m if limited to 2°C (*low confidence*). {*3.1.3, Figure 3.4*} (*Box SPM.1*)

B.3.2 The likelihood and impacts of abrupt and/or irreversible changes in the climate system, including changes triggered when tipping points are reached, increase with further global warming (*high confidence*). As warming levels increase, so do the risks of species extinction or irreversible loss of biodiversity in ecosystems including forests (*medium confidence*), coral reefs (*very high confidence*) and in Arctic regions (*high confidence*). At sustained warming levels between 2°C and 3°C, the Greenland and West Antarctic ice sheets will be lost almost completely and irreversibly over multiple millennia, causing several metres of sea level rise *(limited evidence)*. The probability and rate of ice mass loss increase with higher global surface temperatures (*high confidence*). {*3.1.2, 3.1.3*}

B.3.3 The probability of low-likelihood outcomes associated with potentially very large impacts increases with higher global warming levels (*high confidence*). Due to deep uncertainty linked to ice-sheet processes, global mean sea level rise above the *likely* range – approaching 2 m by 2100 and in excess of 15 m by 2300 under the very high GHG emissions scenario (SSP5-8.5) (*low confidence*) – cannot be excluded. There is *medium confidence* that the Atlantic Meridional Overturning Circulation will not collapse abruptly before 2100, but if it were to occur, it would *very likely* cause abrupt shifts in regional weather patterns, and large impacts on ecosystems and human activities. {*3.1.3*} (*Box SPM.1*)

Adaptation Options and their Limits in a Warmer World

B.4 Adaptation options that are feasible and effective today will become constrained and less effective with increasing global warming. With increasing global warming, losses and damages will increase and additional human and natural systems will reach adaptation limits. Maladaptation can be avoided by flexible, multi-sectoral, inclusive, long-term planning and implementation of adaptation actions, with co-benefits to many sectors and systems. (*high confidence*) {*3.2, 4.1, 4.2, 4.3*}

B.4.1 The effectiveness of adaptation, including ecosystem-based and most water-related options, will decrease with increasing warming. The feasibility and effectiveness of options increase with integrated, multi-sectoral solutions that differentiate responses based on climate risk, cut across systems and address social inequities. As adaptation options often have long implementation times, long-term planning increases their efficiency. (*high confidence*) {*3.2*, *Figure 3.4*, *4.1*, *4.2*}

B.4.2 With additional global warming, limits to adaptation and losses and damages, strongly concentrated among vulnerable populations, will become increasingly difficult to avoid (*high confidence*). Above 1.5°C of global warming, limited freshwater resources pose potential hard adaptation limits for small islands and for regions dependent on glacier and snow melt (*medium confidence*). Above that level, ecosystems such as some warm-water coral reefs, coastal wetlands, rainforests, and polar and mountain ecosystems will have reached or surpassed hard adaptation limits and as a consequence, some Ecosystem-based Adaptation measures will also lose their effectiveness (*high confidence*). {*2.3.2*, *3.2*, *4.3*}

B.4.3 Actions that focus on sectors and risks in isolation and on short-term gains often lead to maladaptation over the long term, creating lock-ins of vulnerability, exposure and risks that are difficult to change. For example, seawalls effectively reduce impacts to people and assets in the short term but can also result in lock-ins and increase exposure to climate risks in the long term unless they are integrated into a long-term adaptive plan. Maladaptive responses can worsen existing inequities especially for Indigenous Peoples and marginalised groups and decrease ecosystem and biodiversity resilience. Maladaptation can be avoided by flexible, multi-sectoral, inclusive, long-term planning and implementation of adaptation actions, with co-benefits to many sectors and systems. (*high confidence*) {*2.3.2*, *3.2*}

Carbon Budgets and Net Zero Emissions

B.5 Limiting human-caused global warming requires net zero CO_2 emissions. Cumulative carbon emissions until the time of reaching net zero CO_2 emissions and the level of greenhouse gas emission reductions this decade largely determine whether warming can be limited to 1.5°C or 2°C (*high confidence*). Projected CO_2 emissions from existing fossil fuel infrastructure without additional abatement would exceed the remaining carbon budget for 1.5°C (50%) (*high confidence*). {*2.3, 3.1, 3.3, Table 3.1*}

B.5.1 From a physical science perspective, limiting human-caused global warming to a specific level requires limiting cumulative CO_2 emissions, reaching at least net zero CO_2 emissions, along with strong reductions in other greenhouse gas emissions. Reaching net zero GHG emissions primarily requires deep reductions in CO_2, methane, and other GHG emissions, and implies net negative CO_2 emissions[39]. Carbon dioxide removal (CDR) will be necessary to achieve net negative CO_2 emissions (see B.6). Net zero GHG emissions, if sustained, are projected to result in a gradual decline in global surface temperatures after an earlier peak. (*high confidence*) {*3.1.1*, *3.3.1*, *3.3.2*, *3.3.3*, *Table 3.1*, *Cross-Section Box.1*}

B.5.2 For every 1000 $GtCO_2$ emitted by human activity, global surface temperature rises by 0.45°C (best estimate, with a *likely* range from 0.27°C to 0.63°C). The best estimates of the remaining carbon budgets from the beginning of 2020 are 500 $GtCO_2$ for a 50% likelihood of limiting global warming to 1.5°C and 1150 $GtCO_2$ for a 67% likelihood of limiting warming to 2°C[40]. The stronger the reductions in non-CO_2 emissions, the lower the resulting temperatures are for a given remaining carbon budget or the larger remaining carbon budget for the same level of temperature change[41]. {*3.3.1*}

39 Net zero GHG emissions defined by the 100-year global warming potential. See footnote 9.

40 Global databases make different choices about which emissions and removals occurring on land are considered anthropogenic. Most countries report their anthropogenic land CO_2 fluxes including fluxes due to human-caused environmental change (e.g., CO_2 fertilisation) on 'managed' land in their national GHG inventories. Using emissions estimates based on these inventories, the remaining carbon budgets must be correspondingly reduced. {*3.3.1*}

41 For example, remaining carbon budgets could be 300 or 600 $GtCO_2$ for 1.5°C (50%), respectively for high and low non-CO_2 emissions, compared to 500 $GtCO_2$ in the central case. {*3.3.1*}

Summary for Policymakers

B.5.3 If the annual CO_2 emissions between 2020–2030 stayed, on average, at the same level as 2019, the resulting cumulative emissions would almost exhaust the remaining carbon budget for 1.5°C (50%), and deplete more than a third of the remaining carbon budget for 2°C (67%). Estimates of future CO_2 emissions from existing fossil fuel infrastructures without additional abatement[42] already exceed the remaining carbon budget for limiting warming to 1.5°C (50%) (*high confidence*). Projected cumulative future CO_2 emissions over the lifetime of existing and planned fossil fuel infrastructure, if historical operating patterns are maintained and without additional abatement[43], are approximately equal to the remaining carbon budget for limiting warming to 2°C with a likelihood of 83%[44] (*high confidence*). {*2.3.1*, *3.3.1*, *Figure 3.5*}

B.5.4 Based on central estimates only, historical cumulative net CO_2 emissions between 1850 and 2019 amount to about four fifths[45] of the total carbon budget for a 50% probability of limiting global warming to 1.5°C (central estimate about 2900 $GtCO_2$), and to about two thirds[46] of the total carbon budget for a 67% probability to limit global warming to 2°C (central estimate about 3550 $GtCO_2$). {*3.3.1*, *Figure 3.5*}

Mitigation Pathways

B.6 All global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and those that limit warming to 2°C (>67%), involve rapid and deep and, in most cases, immediate greenhouse gas emissions reductions in all sectors this decade. Global net zero CO_2 emissions are reached for these pathway categories, in the early 2050s and around the early 2070s, respectively. (*high confidence*) {*3.3, 3.4, 4.1, 4.5, Table 3.1*} (*Figure SPM.5, Box SPM.1*)

B.6.1 Global modelled pathways provide information on limiting warming to different levels; these pathways, particularly their sectoral and regional aspects, depend on the assumptions described in Box SPM.1. Global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot or limit warming to 2°C (>67%) are characterized by deep, rapid, and, in most cases, immediate GHG emissions reductions. Pathways that limit warming to 1.5 °C (>50%) with no or limited overshoot reach net zero CO_2 in the early 2050s, followed by net negative CO_2 emissions. Those pathways that reach net zero GHG emissions do so around the 2070s. Pathways that limit warming to 2 °C (>67%) reach net zero CO_2 emissions in the early 2070s. Global GHG emissions are projected to peak between 2020 and at the latest before 2025 in global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and in those that limit warming to 2°C (>67%) and assume immediate action. (*high confidence*) {*3.3.2*, *3.3.4*, *4.1*, *Table 3.1*, *Figure 3.6*} (*Table SPM.1*)

---

42 Abatement here refers to human interventions that reduce the amount of greenhouse gases that are released from fossil fuel infrastructure to the atmosphere.

43 Ibid.

44 WGI provides carbon budgets that are in line with limiting global warming to temperature limits with different likelihoods, such as 50%, 67% or 83%. {*3.3.1*}

45 Uncertainties for total carbon budgets have not been assessed and could affect the specific calculated fractions.

46 Ibid.

Table SPM.1: Greenhouse gas and CO_2 emission reductions from 2019, median and 5-95 percentiles. {*3.3.1*, *4.1*, *Table 3.1*, *Figure 2.5*, *Box SPM.1*}

		Reductions from 2019 emission levels (%)			
		2030	2035	2040	2050
Limit warming to1.5°C (>50%) with no or limited overshoot	GHG	43 [34-60]	60 [49-77]	69 [58-90]	84 [73-98]
	CO_2	48 [36-69]	65 [50-96]	80 [61-109]	99 [79-119]
Limit warming to 2°C (>67%)	GHG	21 [1-42]	35 [22-55]	46 [34-63]	64 [53-77]
	CO_2	22 [1-44]	37 [21-59]	51 [36-70]	73 [55-90]

B.6.2 Reaching net zero CO_2 or GHG emissions primarily requires deep and rapid reductions in gross emissions of CO_2, as well as substantial reductions of non-CO_2 GHG emissions (*high confidence*). For example, in modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, global methane emissions are reduced by 34 [21–57] % by 2030 relative to 2019. However, some hard-to-abate residual GHG emissions (e.g., some emissions from agriculture, aviation, shipping, and industrial processes) remain and would need to be counterbalanced by deployment of CDR methods to achieve net zero CO_2 or GHG emissions (*high confidence*). As a result, net zero CO_2 is reached earlier than net zero GHGs (*high confidence*). {*3.3.2*, *3.3.3*, *Table 3.1*, *Figure 3.5*} (*Figure SPM.5*)

B.6.3 Global modelled mitigation pathways reaching net zero CO_2 and GHG emissions include transitioning from fossil fuels without carbon capture and storage (CCS) to very low- or zero-carbon energy sources, such as renewables or fossil fuels with CCS, demand-side measures and improving efficiency, reducing non-CO_2 GHG emissions, and CDR[47]. In most global modelled pathways, land-use change and forestry (via reforestation and reduced deforestation) and the energy supply sector reach net zero CO_2 emissions earlier than the buildings, industry and transport sectors. (*high confidence*) {*3.3.3*, *4.1*, *4.5*, *Figure 4.1*} (*Figure SPM.5*, *Box SPM.1*)

B.6.4 Mitigation options often have synergies with other aspects of sustainable development, but some options can also have trade-offs. There are potential synergies between sustainable development and, for instance, energy efficiency and renewable energy. Similarly, depending on the context[48], biological CDR methods like reforestation, improved forest management, soil carbon sequestration, peatland restoration and coastal blue carbon management can enhance biodiversity and ecosystem functions, employment and local livelihoods. However, afforestation or production of biomass crops can have adverse socio-economic and environmental impacts, including on biodiversity, food and water security, local livelihoods and the rights of Indigenous Peoples, especially if implemented at large scales and where land tenure is insecure. Modelled pathways that assume using resources more efficiently or that shift global development towards sustainability include fewer challenges, such as less dependence on CDR and pressure on land and biodiversity. (*high confidence*) {*3.4.1*}

[47] CCS is an option to reduce emissions from large-scale fossil-based energy and industry sources provided geological storage is available. When CO_2 is captured directly from the atmosphere (DACCS), or from biomass (BECCS), CCS provides the storage component of these CDR methods. CO_2 capture and subsurface injection is a mature technology for gas processing and enhanced oil recovery. In contrast to the oil and gas sector, CCS is less mature in the power sector, as well as in cement and chemicals production, where it is a critical mitigation option. The technical geological storage capacity is estimated to be on the order of 1000 $GtCO_2$, which is more than the CO_2 storage requirements through 2100 to limit global warming to 1.5°C, although the regional availability of geological storage could be a limiting factor. If the geological storage site is appropriately selected and managed, it is estimated that the CO_2 can be permanently isolated from the atmosphere. Implementation of CCS currently faces technological, economic, institutional, ecological-environmental and socio-cultural barriers. Currently, global rates of CCS deployment are far below those in modelled pathways limiting global warming to 1.5°C to 2°C. Enabling conditions such as policy instruments, greater public support and technological innovation could reduce these barriers. (*high confidence*) {*3.3.3*}

[48] The impacts, risks, and co-benefits of CDR deployment for ecosystems, biodiversity and people will be highly variable depending on the method, site-specific context, implementation and scale (*high confidence*).

Limiting warming to 1.5°C and 2°C involves rapid, deep and in most cases immediate greenhouse gas emission reductions

Net zero CO_2 and net zero GHG emissions can be achieved through strong reductions across all sectors

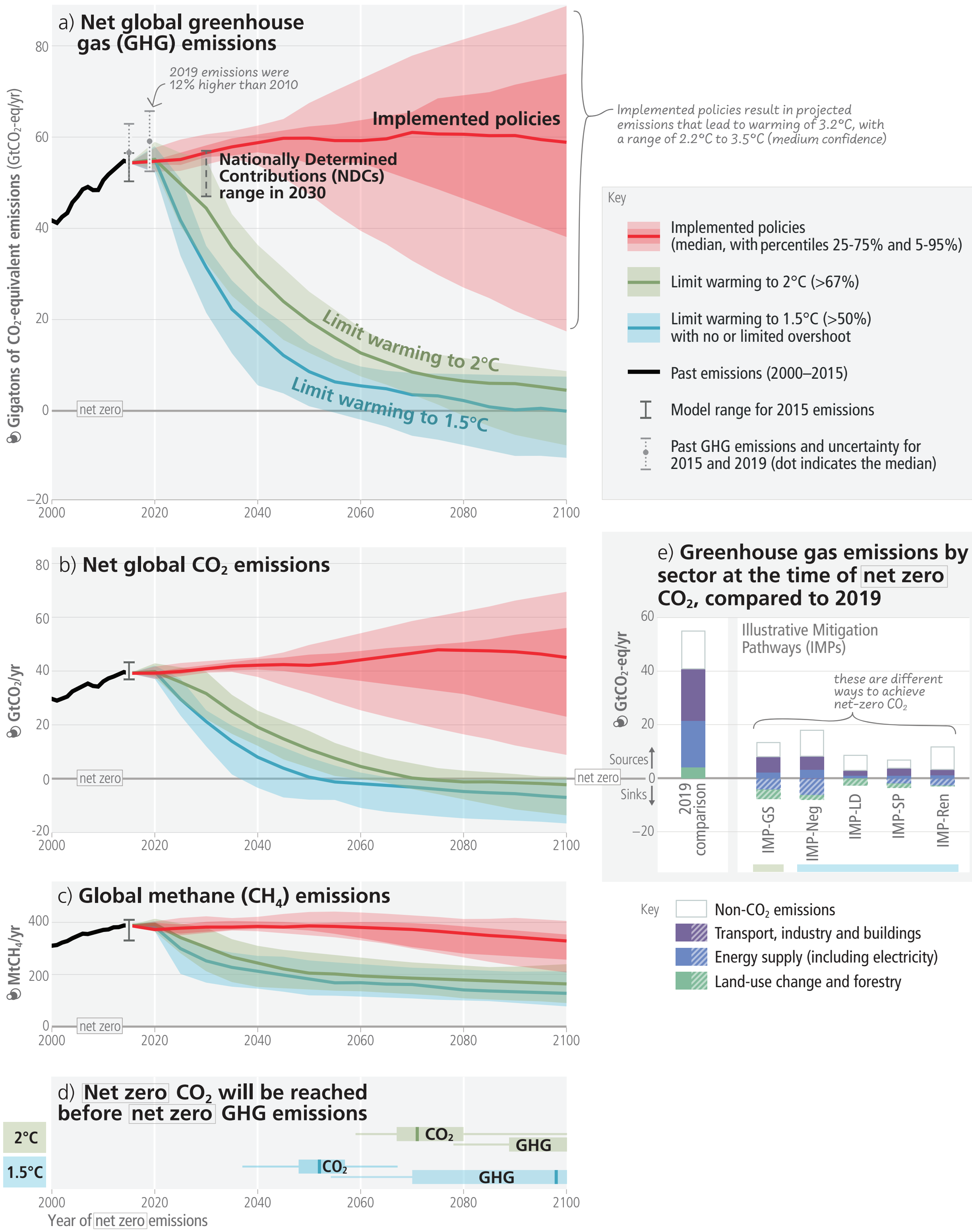


Figure SPM.5: Global emissions pathways consistent with implemented policies and mitigation strategies. Panels (a), (b) and **(c)** show the development of global GHG, CO_2 and methane emissions in modelled pathways, while **panel (d)** shows the associated timing of when GHG and CO_2 emissions reach net zero. Coloured ranges denote the 5th to 95th percentile across the global modelled pathways falling within a given category as described in Box SPM.1. The red ranges depict emissions pathways assuming policies that were implemented by the end of 2020. Ranges of modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot are shown in light blue (category C1) and pathways that limit warming to 2°C (>67%) are shown in green (category C3). Global emission pathways that would limit warming to 1.5°C (>50%) with no or limited overshoot and also reach net zero GHG in the second half of the century do so between 2070–2075. **Panel (e)** shows the sectoral contributions of CO_2 and non-CO_2 emissions sources and sinks at the time when net zero CO_2 emissions are reached in illustrative mitigation pathways (IMPs) consistent with limiting warming to 1.5°C with a high reliance on net negative emissions (IMP-Neg) ("high overshoot"), high resource efficiency (IMP-LD), a focus on sustainable development (IMP-SP), renewables (IMP-Ren) and limiting warming to 2°C with less rapid mitigation initially followed by a gradual strengthening (IMP-GS). Positive and negative emissions for different IMPs are compared to GHG emissions from the year 2019. Energy supply (including electricity) includes bioenergy with carbon dioxide capture and storage and direct air carbon dioxide capture and storage. CO_2 emissions from land-use change and forestry can only be shown as a net number as many models do not report emissions and sinks of this category separately. {*Figure 3.6, 4.1*} (*Box SPM.1*)

Overshoot: Exceeding a Warming Level and Returning

B.7 If warming exceeds a specified level such as 1.5°C, it could gradually be reduced again by achieving and sustaining net negative global CO_2 emissions. This would require additional deployment of carbon dioxide removal, compared to pathways without overshoot, leading to greater feasibility and sustainability concerns. Overshoot entails adverse impacts, some irreversible, and additional risks for human and natural systems, all growing with the magnitude and duration of overshoot. (*high confidence*) {*3.1, 3.3, 3.4, Table 3.1, Figure 3.6*}

B.7.1 Only a small number of the most ambitious global modelled pathways limit global warming to 1.5°C (>50%) by 2100 without exceeding this level temporarily. Achieving and sustaining net negative global CO_2 emissions, with annual rates of CDR greater than residual CO_2 emissions, would gradually reduce the warming level again (*high confidence*). Adverse impacts that occur during this period of overshoot and cause additional warming via feedback mechanisms, such as increased wildfires, mass mortality of trees, drying of peatlands, and permafrost thawing, weakening natural land carbon sinks and increasing releases of GHGs would make the return more challenging (*medium confidence*). {*3.3.2, 3.3.4, Table 3.1, Figure 3.6*} (*Box SPM.1*)

B.7.2 The higher the magnitude and the longer the duration of overshoot, the more ecosystems and societies are exposed to greater and more widespread changes in climatic impact-drivers, increasing risks for many natural and human systems. Compared to pathways without overshoot, societies would face higher risks to infrastructure, low-lying coastal settlements, and associated livelihoods. Overshooting 1.5°C will result in irreversible adverse impacts on certain ecosystems with low resilience, such as polar, mountain, and coastal ecosystems, impacted by ice-sheet melt, glacier melt, or by accelerating and higher committed sea level rise. (*high confidence*) {*3.1.2, 3.3.4*}

B.7.3 The larger the overshoot, the more net negative CO_2 emissions would be needed to return to 1.5°C by 2100. Transitioning towards net zero CO_2 emissions faster and reducing non-CO_2 emissions such as methane more rapidly would limit peak warming levels and reduce the requirement for net negative CO_2 emissions, thereby reducing feasibility and sustainability concerns, and social and environmental risks associated with CDR deployment at large scales. (*high confidence*) {*3.3.3, 3.3.4, 3.4.1, Table 3.1*}

C. Responses in the Near Term

Urgency of Near-Term Integrated Climate Action

C.1 Climate change is a threat to human well-being and planetary health (*very high confidence*). There is a rapidly closing window of opportunity to secure a liveable and sustainable future for all (*very high confidence*). Climate resilient development integrates adaptation and mitigation to advance sustainable development for all, and is enabled by increased international cooperation including improved access to adequate financial resources, particularly for vulnerable regions, sectors and groups, and inclusive governance and coordinated policies (*high confidence*). The choices and actions implemented in this decade will have impacts now and for thousands of years (*high confidence*). {*3.1, 3.3, 4.1, 4.2, 4.3, 4.4, 4.7, 4.8, 4.9, Figure 3.1, Figure 3.3, Figure 4.2*} (*Figure SPM.1, Figure SPM.6*)

C.1.1 Evidence of observed adverse impacts and related losses and damages, projected risks, levels and trends in vulnerability and adaptation limits, demonstrate that worldwide climate resilient development action is more urgent than previously assessed in AR5. Climate resilient development integrates adaptation and GHG mitigation to advance sustainable development for all. Climate resilient development pathways have been constrained by past development, emissions and climate change and are progressively constrained by every increment of warming, in particular beyond 1.5°C. (*very high confidence*) {*3.4*, *3.4.2*, *4.1*}

C.1.2 Government actions at sub-national, national and international levels, with civil society and the private sector, play a crucial role in enabling and accelerating shifts in development pathways towards sustainability and climate resilient development (*very high confidence*). Climate resilient development is enabled when governments, civil society and the private sector make inclusive development choices that prioritize risk reduction, equity and justice, and when decision-making processes, finance and actions are integrated across governance levels, sectors, and timeframes (*very high confidence*). Enabling conditions are differentiated by national, regional and local circumstances and geographies, according to capabilities, and include: political commitment and follow-through, coordinated policies, social and international cooperation, ecosystem stewardship, inclusive governance, knowledge diversity, technological innovation, monitoring and evaluation, and improved access to adequate financial resources, especially for vulnerable regions, sectors and communities (*high confidence*). {*3.4*, *4.2*, *4.4*, *4.5*, *4.7*, *4.8*} (*Figure SPM.6*)

C.1.3 Continued emissions will further affect all major climate system components, and many changes will be irreversible on centennial to millennial time scales and become larger with increasing global warming. Without urgent, effective, and equitable mitigation and adaptation actions, climate change increasingly threatens ecosystems, biodiversity, and the livelihoods, health and well-being of current and future generations. (*high confidence*) {*3.1.3*, *3.3.3*, *3.4.1*, *Figure 3.4*, *4.1*, *4.2*, *4.3*, *4.4*} (*Figure SPM.1*, *Figure SPM.6*)

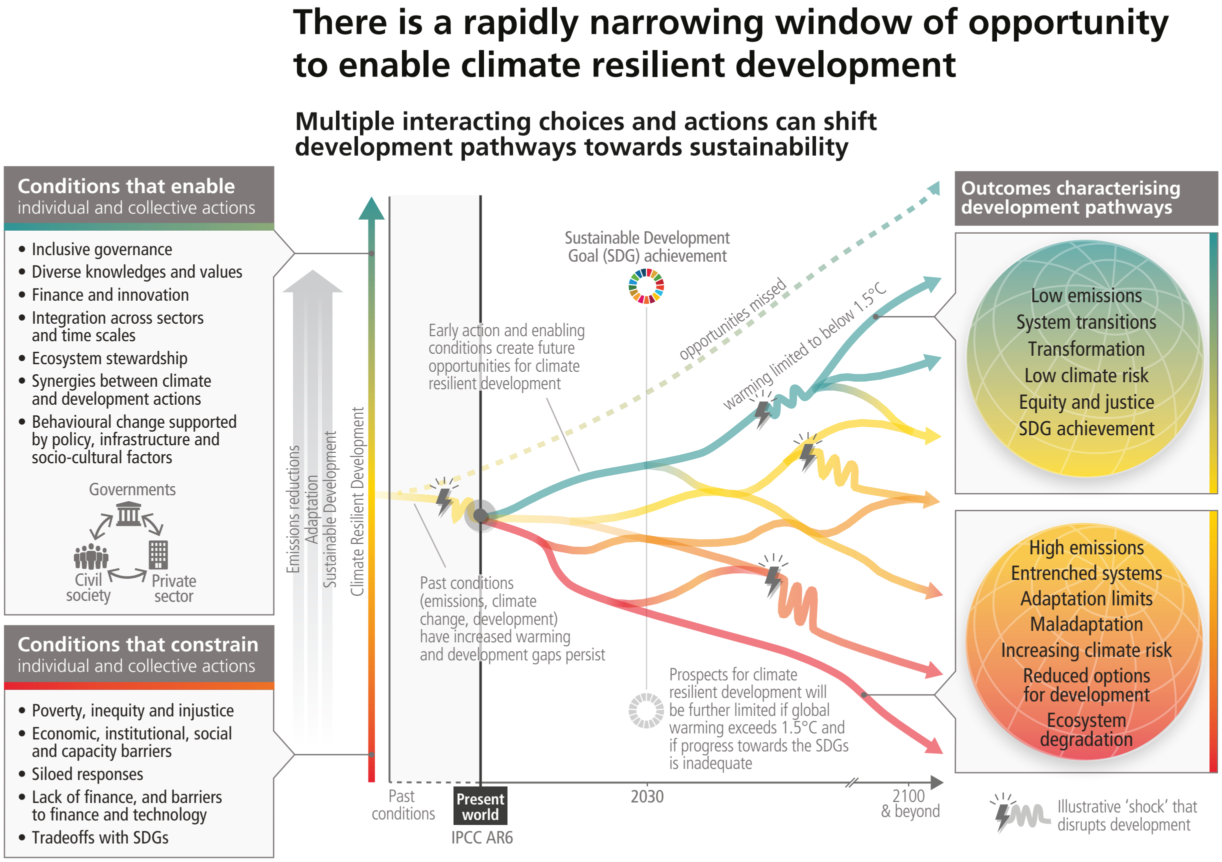


Figure SPM.6: The illustrative development pathways (red to green) and associated outcomes (right panel) show that there is a rapidly narrowing window of opportunity to secure a liveable and sustainable future for all. Climate resilient development is the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development. Diverging pathways illustrate that interacting choices and actions made by diverse government, private sector and civil society actors can advance climate resilient development, shift pathways towards sustainability, and enable lower emissions and adaptation. Diverse knowledge and values include cultural values, Indigenous Knowledge, local knowledge, and scientific knowledge. Climatic and non-climatic events, such as droughts, floods or pandemics, pose more severe shocks to pathways with lower climate resilient development (red to yellow) than to pathways with higher climate resilient development (green). There are limits to adaptation and adaptive capacity for some human and natural systems at global warming of 1.5°C, and with every increment of warming, losses and damages will increase. The development pathways taken by countries at all stages of economic development impact GHG emissions and mitigation challenges and opportunities, which vary across countries and regions. Pathways and opportunities for action are shaped by previous actions (or inactions and opportunities missed; dashed pathway) and enabling and constraining conditions (left panel), and take place in the context of climate risks, adaptation limits and development gaps. The longer emissions reductions are delayed, the fewer effective adaptation options. {*Figure 4.2, 3.1, 3.2, 3.4, 4.2, 4.4, 4.5, 4.6, 4.9*}

The Benefits of Near-Term Action

C.2 Deep, rapid, and sustained mitigation and accelerated implementation of adaptation actions in this decade would reduce projected losses and damages for humans and ecosystems (*very high confidence*), and deliver many co-benefits, especially for air quality and health (*high confidence*). Delayed mitigation and adaptation action would lock in high-emissions infrastructure, raise risks of stranded assets and cost-escalation, reduce feasibility, and increase losses and damages (*high confidence*). Near-term actions involve high up-front investments and potentially disruptive changes that can be lessened by a range of enabling policies (*high confidence*). {*2.1, 2.2, 3.1, 3.2, 3.3, 3.4, 4.1, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8*}

C.2.1 Deep, rapid, and sustained mitigation and accelerated implementation of adaptation actions in this decade would reduce future losses and damages related to climate change for humans and ecosystems (*very high confidence*). As adaptation options often have long implementation times, accelerated implementation of adaptation in this decade is important to close adaptation gaps (*high confidence*). Comprehensive, effective, and innovative responses integrating adaptation and mitigation can harness synergies and reduce trade-offs between adaptation and mitigation (*high confidence*). {*4.1, 4.2, 4.3*}

C.2.2 Delayed mitigation action will further increase global warming and losses and damages will rise and additional human and natural systems will reach adaptation limits. Challenges from delayed adaptation and mitigation actions include the risk of cost escalation, lock-in of infrastructure, stranded assets, and reduced feasibility and effectiveness of adaptation and mitigation options. Without rapid, deep and sustained mitigation and accelerated adaptation actions, losses and damages will continue to increase, including projected adverse impacts in Africa, LDCs, SIDS, Central and South America[49], Asia and the Arctic, and will disproportionately affect the most vulnerable populations. *(high confidence)* {*2.1.2*, *3.1.2*, *3.2*, *3.3.1*, *3.3.3*, *4.1*, *4.2*, *4.3*} (*Figure SPM.3*, *Figure SPM.4*)

C.2.3 Accelerated climate action can also provide co-benefits (see also C.4) (*high confidence*). Many mitigation actions would have benefits for health through lower air pollution, active mobility (e.g., walking, cycling), and shifts to sustainable healthy diets (*high confidence*). Strong, rapid and sustained reductions in methane emissions can limit near-term warming and improve air quality by reducing global surface ozone (*high confidence*). Adaptation can generate multiple additional benefits such as improving agricultural productivity, innovation, health and well-being, food security, livelihood, and biodiversity conservation (*very high confidence*). {*4.2*, *4.5.4*, *4.5.5*, *4.6*}

C.2.4 Cost-benefit analysis remains limited in its ability to represent all avoided damages from climate change (*high confidence*). The economic benefits for human health from air quality improvement arising from mitigation action can be of the same order of magnitude as mitigation costs, and potentially even larger (*medium confidence*). Even without accounting for all the benefits of avoiding potential damages, the global economic and social benefit of limiting global warming to 2°C exceeds the cost of mitigation in most of the assessed literature (*medium confidence*)[50]. More rapid climate change mitigation, with emissions peaking earlier, increases co-benefits and reduces feasibility risks and costs in the long-term, but requires higher up-front investments (*high confidence*). {*3.4.1*, *4.2*}

C.2.5 Ambitious mitigation pathways imply large and sometimes disruptive changes in existing economic structures, with significant distributional consequences within and between countries. To accelerate climate action, the adverse consequences of these changes can be moderated by fiscal, financial, institutional and regulatory reforms and by integrating climate actions with macroeconomic policies through (i) economy-wide packages, consistent with national circumstances, supporting sustainable low-emission growth paths; (ii) climate resilient safety nets and social protection; and (iii) improved access to finance for low-emissions infrastructure and technologies, especially in developing countries. (*high confidence*) {*4.2*, *4.4*, *4.7*, *4.8.1*}

---

[49] The southern part of Mexico is included in the climatic subregion South Central America (SCA) for WGI. Mexico is assessed as part of North America for WGII. The climate change literature for the SCA region occasionally includes Mexico, and in those cases WGII assessment makes reference to Latin America. Mexico is considered part of Latin America and the Caribbean for WGIII.

[50] The evidence is too limited to make a similar robust conclusion for limiting warming to 1.5°C. Limiting global warming to 1.5°C instead of 2°C would increase the costs of mitigation, but also increase the benefits in terms of reduced impacts and related risks, and reduced adaptation needs (*high confidence*).

There are multiple opportunities for scaling up climate action

a) **Feasibility of climate responses and adaptation, and potential of mitigation options in the near term**

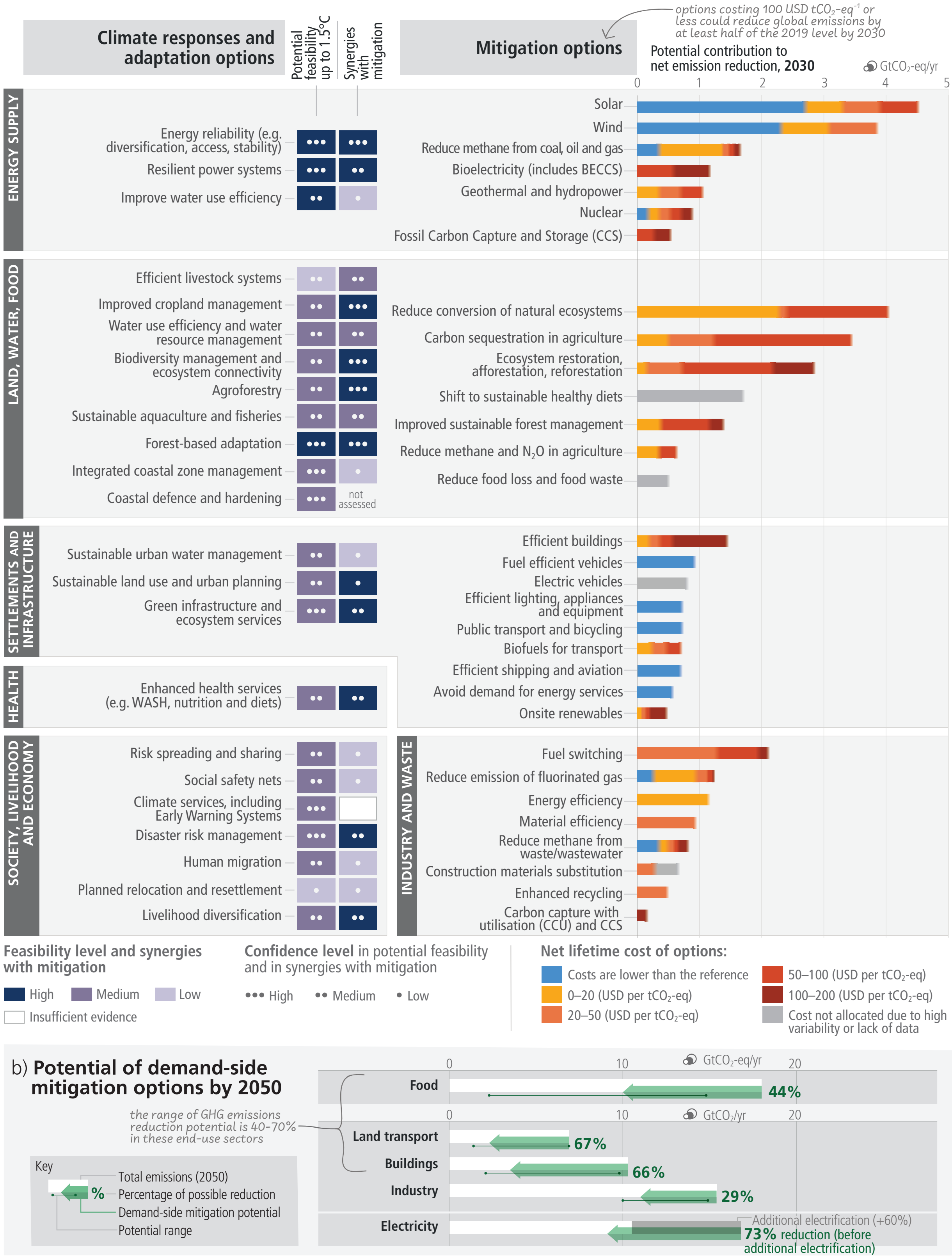


Figure SPM.7: Multiple Opportunities for scaling up climate action. Panel (a) presents selected mitigation and adaptation options across different systems. The left-hand side of panel a shows climate responses and adaptation options assessed for their multidimensional feasibility at global scale, in the near term and up to 1.5°C global warming. As literature above 1.5°C is limited, feasibility at higher levels of warming may change, which is currently not possible to assess robustly. The term response is used here in addition to adaptation because some responses, such as migration, relocation and resettlement may or may not be considered to be adaptation. Forest based adaptation includes sustainable forest management, forest conservation and restoration, reforestation and afforestation. WASH refers to water, sanitation and hygiene. Six feasibility dimensions (economic, technological, institutional, social, environmental and geophysical) were used to calculate the potential feasibility of climate responses and adaptation options, along with their synergies with mitigation. For potential feasibility and feasibility dimensions, the figure shows high, medium, or low feasibility. Synergies with mitigation are identified as high, medium, and low. The right-hand side of Panel a provides an overview of selected mitigation options and their estimated costs and potentials in 2030. Costs are net lifetime discounted monetary costs of avoided GHG emissions calculated relative to a reference technology. Relative potentials and costs will vary by place, context and time and in the longer term compared to 2030. The potential (horizontal axis) is the net GHG emission reduction (sum of reduced emissions and/or enhanced sinks) broken down into cost categories (coloured bar segments) relative to an emission baseline consisting of current policy (around 2019) reference scenarios from the AR6 scenarios database. The potentials are assessed independently for each option and are not additive. Health system mitigation options are included mostly in settlement and infrastructure (e.g., efficient healthcare buildings) and cannot be identified separately. Fuel switching in industry refers to switching to electricity, hydrogen, bioenergy and natural gas. Gradual colour transitions indicate uncertain breakdown into cost categories due to uncertainty or heavy context dependency. The uncertainty in the total potential is typically 25–50%. **Panel (b)** displays the indicative potential of demand-side mitigation options for 2050. Potentials are estimated based on approximately 500 bottom-up studies representing all global regions. The baseline (white bar) is provided by the sectoral mean GHG emissions in 2050 of the two scenarios (IEA-STEPS and IP_ModAct) consistent with policies announced by national governments until 2020. The green arrow represents the demand-side emissions reductions potentials. The range in potential is shown by a line connecting dots displaying the highest and the lowest potentials reported in the literature. Food shows demand-side potential of socio-cultural factors and infrastructure use, and changes in land-use patterns enabled by change in food demand. Demand-side measures and new ways of end-use service provision can reduce global GHG emissions in end-use sectors (buildings, land transport, food) by 40–70% by 2050 compared to baseline scenarios, while some regions and socioeconomic groups require additional energy and resources. The last row shows how demand-side mitigation options in other sectors can influence overall electricity demand. The dark grey bar shows the projected increase in electricity demand above the 2050 baseline due to increasing electrification in the other sectors. Based on a bottom-up assessment, this projected increase in electricity demand can be avoided through demand-side mitigation options in the domains of infrastructure use and socio-cultural factors that influence electricity usage in industry, land transport, and buildings (green arrow). {*Figure 4.4*}

Mitigation and Adaptation Options across Systems

C.3 Rapid and far-reaching transitions across all sectors and systems are necessary to achieve deep and sustained emissions reductions and secure a liveable and sustainable future for all. These system transitions involve a significant upscaling of a wide portfolio of mitigation and adaptation options. Feasible, effective, and low-cost options for mitigation and adaptation are already available, with differences across systems and regions. (*high confidence*) {*4.1, 4.5, 4.6*} (*Figure SPM.7*)

C.3.1 The systemic change required to achieve rapid and deep emissions reductions and transformative adaptation to climate change is unprecedented in terms of scale, but not necessarily in terms of speed (*medium confidence*). Systems transitions include: deployment of low- or zero-emission technologies; reducing and changing demand through infrastructure design and access, socio-cultural and behavioural changes, and increased technological efficiency and adoption; social protection, climate services or other services; and protecting and restoring ecosystems (*high confidence*). Feasible, effective, and low-cost options for mitigation and adaptation are already available (*high confidence*). The availability, feasibility and potential of mitigation and adaptation options in the near term differs across systems and regions (*very high confidence*). {*4.1, 4.5.1 to 4.5.6*} (*Figure SPM.7*)

Energy Systems

C.3.2 Net zero CO_2 energy systems entail: a substantial reduction in overall fossil fuel use, minimal use of unabated fossil fuels[51], and use of carbon capture and storage in the remaining fossil fuel systems; electricity systems that emit no net CO_2; widespread electrification; alternative energy carriers in applications less amenable to electrification; energy conservation and efficiency; and greater integration across the energy system (*high confidence*). Large contributions to emissions reductions with costs less than USD 20 tCO_2-eq^{-1} come from solar and wind energy, energy efficiency improvements, and methane emissions reductions (coal mining, oil and gas, waste) (*medium confidence*). There are feasible adaptation options that support infrastructure resilience, reliable power systems and efficient water use for existing and new energy generation systems (*very high confidence*). Energy generation diversification (e.g., via wind, solar, small scale hydropower) and demand-side management (e.g., storage and energy efficiency improvements) can increase energy reliability and reduce vulnerabilities to climate change (*high confidence*). Climate responsive energy markets, updated design standards on energy assets according to current and projected climate change, smart-grid technologies, robust transmission systems and improved capacity to respond to supply deficits have high feasibility in the medium to long term, with mitigation co-benefits (*very high confidence*). {*4.5.1*} (*Figure SPM.7*)

[51] In this context, 'unabated fossil fuels' refers to fossil fuels produced and used without interventions that substantially reduce the amount of GHG emitted throughout the life cycle; for example, capturing 90% or more CO_2 from power plants, or 50–80% of fugitive methane emissions from energy supply.

Industry and Transport

C.3.3 Reducing industry GHG emissions entails coordinated action throughout value chains to promote all mitigation options, including demand management, energy and materials efficiency, circular material flows, as well as abatement technologies and transformational changes in production processes (*high confidence*). In transport, sustainable biofuels, low-emissions hydrogen, and derivatives (including ammonia and synthetic fuels) can support mitigation of CO_2 emissions from shipping, aviation, and heavy-duty land transport but require production process improvements and cost reductions (*medium confidence*). Sustainable biofuels can offer additional mitigation benefits in land-based transport in the short and medium term (*medium confidence*). Electric vehicles powered by low-GHG emissions electricity have large potential to reduce land-based transport GHG emissions, on a life cycle basis (*high confidence*). Advances in battery technologies could facilitate the electrification of heavy-duty trucks and compliment conventional electric rail systems (*medium confidence*). The environmental footprint of battery production and growing concerns about critical minerals can be addressed by material and supply diversification strategies, energy and material efficiency improvements, and circular material flows (*medium confidence*). {*4.5.2, 4.5.3*} (*Figure SPM.7*)

Cities, Settlements and Infrastructure

C.3.4 Urban systems are critical for achieving deep emissions reductions and advancing climate resilient development (*high confidence*). Key adaptation and mitigation elements in cities include considering climate change impacts and risks (e.g., through climate services) in the design and planning of settlements and infrastructure; land use planning to achieve compact urban form, co-location of jobs and housing; supporting public transport and active mobility (e.g., walking and cycling); the efficient design, construction, retrofit, and use of buildings; reducing and changing energy and material consumption; sufficiency[52]; material substitution; and electrification in combination with low emissions sources (*high confidence*). Urban transitions that offer benefits for mitigation, adaptation, human health and well-being, ecosystem services, and vulnerability reduction for low-income communities are fostered by inclusive long-term planning that takes an integrated approach to physical, natural and social infrastructure (*high confidence*). Green/natural and blue infrastructure supports carbon uptake and storage and either singly or when combined with grey infrastructure can reduce energy use and risk from extreme events such as heatwaves, flooding, heavy precipitation and droughts, while generating co-benefits for health, well-being and livelihoods (*medium confidence*). {*4.5.3*}

Land, Ocean, Food, and Water

C.3.5 Many agriculture, forestry, and other land use (AFOLU) options provide adaptation and mitigation benefits that could be upscaled in the near term across most regions. Conservation, improved management, and restoration of forests and other ecosystems offer the largest share of economic mitigation potential, with reduced deforestation in tropical regions having the highest total mitigation potential. Ecosystem restoration, reforestation, and afforestation can lead to trade-offs due to competing demands on land. Minimizing trade-offs requires integrated approaches to meet multiple objectives including food security. Demand-side measures (shifting to sustainable healthy diets[53] and reducing food loss/waste) and sustainable agricultural intensification can reduce ecosystem conversion, and methane and nitrous oxide emissions, and free up land for reforestation and ecosystem restoration. Sustainably sourced agricultural and forest products, including long-lived wood products, can be used instead of more GHG-intensive products in other sectors. Effective adaptation options include cultivar improvements, agroforestry, community-based adaptation, farm and landscape diversification, and urban agriculture. These AFOLU response options require integration of biophysical, socioeconomic and other enabling factors. Some options, such as conservation of high-carbon ecosystems (e.g., peatlands, wetlands, rangelands, mangroves and forests), deliver immediate benefits, while others, such as restoration of high-carbon ecosystems, take decades to deliver measurable results. (*high confidence*) {*4.5.4*} (*Figure SPM.7*)

C.3.6 Maintaining the resilience of biodiversity and ecosystem services at a global scale depends on effective and equitable conservation of approximately 30% to 50% of Earth's land, freshwater and ocean areas, including currently near-natural ecosystems (*high confidence*). Conservation, protection and restoration of terrestrial, freshwater, coastal and

52 A set of measures and daily practices that avoid demand for energy, materials, land, and water while delivering human well-being for all within planetary boundaries. {*4.5.3*}

53 'Sustainable healthy diets' promote all dimensions of individuals' health and well-being; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable, as described in FAO and WHO. The related concept of 'balanced diets' refers to diets that feature plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, and animal-sourced food produced in resilient, sustainable and low-GHG emission systems, as described in SRCCL.

ocean ecosystems, together with targeted management to adapt to unavoidable impacts of climate change reduces the vulnerability of biodiversity and ecosystem services to climate change (*high confidence*), reduces coastal erosion and flooding (*high confidence*), and could increase carbon uptake and storage if global warming is limited (*medium confidence*). Rebuilding overexploited or depleted fisheries reduces negative climate change impacts on fisheries (*medium confidence*) and supports food security, biodiversity, human health and well-being (*high confidence*). Land restoration contributes to climate change mitigation and adaptation with synergies via enhanced ecosystem services and with economically positive returns and co-benefits for poverty reduction and improved livelihoods (*high confidence*). Cooperation, and inclusive decision making, with Indigenous Peoples and local communities, as well as recognition of inherent rights of Indigenous Peoples, is integral to successful adaptation and mitigation across forests and other ecosystems (*high confidence*). {*4.5.4, 4.6*} (*Figure SPM.7*)

Health and Nutrition

C.3.7 Human health will benefit from integrated mitigation and adaptation options that mainstream health into food, infrastructure, social protection, and water policies (*very high confidence*). Effective adaptation options exist to help protect human health and well-being, including: strengthening public health programs related to climate-sensitive diseases, increasing health systems resilience, improving ecosystem health, improving access to potable water, reducing exposure of water and sanitation systems to flooding, improving surveillance and early warning systems, vaccine development (*very high confidence*), improving access to mental healthcare, and Heat Health Action Plans that include early warning and response systems (*high confidence*). Adaptation strategies which reduce food loss and waste or support balanced, sustainable healthy diets contribute to nutrition, health, biodiversity and other environmental benefits (*high confidence*). {*4.5.5*} (*Figure SPM.7*)

Society, Livelihoods, and Economies

C.3.8 Policy mixes that include weather and health insurance, social protection and adaptive social safety nets, contingent finance and reserve funds, and universal access to early warning systems combined with effective contingency plans, can reduce vulnerability and exposure of human systems. Disaster risk management, early warning systems, climate services and risk spreading and sharing approaches have broad applicability across sectors. Increasing education including capacity building, climate literacy, and information provided through climate services and community approaches can facilitate heightened risk perception and accelerate behavioural changes and planning. (*high confidence*) {*4.5.6*}

Synergies and Trade-Offs with Sustainable Development

C.4 Accelerated and equitable action in mitigating and adapting to climate change impacts is critical to sustainable development. Mitigation and adaptation actions have more synergies than trade-offs with Sustainable Development Goals. Synergies and trade-offs depend on context and scale of implementation. (*high confidence*) {*3.4, 4.2, 4.4, 4.5, 4.6, 4.9, Figure 4.5*}

C.4.1 Mitigation efforts embedded within the wider development context can increase the pace, depth and breadth of emission reductions (*medium confidence*). Countries at all stages of economic development seek to improve the well-being of people, and their development priorities reflect different starting points and contexts. Different contexts include but are not limited to social, economic, environmental, cultural, political circumstances, resource endowment, capabilities, international environment, and prior development (*high confidence*). In regions with high dependency on fossil fuels for, among other things, revenue and employment generation, mitigating risk for sustainable development requires policies that promote economic and energy sector diversification and considerations of just transitions principles, processes and practices (*high confidence*). Eradicating extreme poverty, energy poverty, and providing decent living standards in low-emitting countries / regions in the context of achieving sustainable development objectives, in the near term, can be achieved without significant global emissions growth (*high confidence*). {*4.4, 4.6, Annex I: Glossary*}

C.4.2 Many mitigation and adaptation actions have multiple synergies with Sustainable Development Goals (SDGs) and sustainable development generally, but some actions can also have trade-offs. Potential synergies with SDGs exceed potential trade-offs; synergies and trade-offs depend on the pace and magnitude of change and the development context including inequalities with consideration of climate justice. Trade-offs can be evaluated and minimised by giving emphasis to capacity building, finance, governance, technology transfer, investments, development, context specific gender-based and other social equity considerations with meaningful participation of Indigenous Peoples, local communities and vulnerable populations. (*high confidence*) {*3.4.1, 4.6, Figure 4.5, 4.9*}

C.4.3 Implementing both mitigation and adaptation actions together and taking trade-offs into account supports co-benefits and synergies for human health and well-being. For example, improved access to clean energy sources and technologies generates health benefits especially for women and children; electrification combined with low-GHG energy, and shifts to active mobility and public transport can enhance air quality, health, employment, and can elicit energy security and deliver equity. (*high confidence*) {*4.2*, *4.5.3*, *4.5.5*, *4.6*, *4.9*}

Equity and Inclusion

C.5 Prioritising equity, climate justice, social justice, inclusion and just transition processes can enable adaptation and ambitious mitigation actions and climate resilient development. Adaptation outcomes are enhanced by increased support to regions and people with the highest vulnerability to climatic hazards. Integrating climate adaptation into social protection programs improves resilience. Many options are available for reducing emission-intensive consumption, including through behavioural and lifestyle changes, with co-benefits for societal well-being. (*high confidence*) {*4.4, 4.5*}

C.5.1 Equity remains a central element in the UN climate regime, notwithstanding shifts in differentiation between states over time and challenges in assessing fair shares. Ambitious mitigation pathways imply large and sometimes disruptive changes in economic structure, with significant distributional consequences, within and between countries. Distributional consequences within and between countries include shifting of income and employment during the transition from high- to low-emissions activities. (*high confidence*) {*4.4*}

C.5.2 Adaptation and mitigation actions that prioritise equity, social justice, climate justice, rights-based approaches, and inclusivity, lead to more sustainable outcomes, reduce trade-offs, support transformative change and advance climate resilient development. Redistributive policies across sectors and regions that shield the poor and vulnerable, social safety nets, equity, inclusion and just transitions, at all scales can enable deeper societal ambitions and resolve trade-offs with sustainable development goals. Attention to equity and broad and meaningful participation of all relevant actors in decision making at all scales can build social trust which builds on equitable sharing of benefits and burdens of mitigation that deepen and widen support for transformative changes. (*high confidence*) {*4.4*}

C.5.3 Regions and people (3.3 to 3.6 billion in number) with considerable development constraints have high vulnerability to climatic hazards (see A.2.2). Adaptation outcomes for the most vulnerable within and across countries and regions are enhanced through approaches focusing on equity, inclusivity and rights-based approaches. Vulnerability is exacerbated by inequity and marginalisation linked to e.g., gender, ethnicity, low incomes, informal settlements, disability, age, and historical and ongoing patterns of inequity such as colonialism, especially for many Indigenous Peoples and local communities. Integrating climate adaptation into social protection programs, including cash transfers and public works programs, is highly feasible and increases resilience to climate change, especially when supported by basic services and infrastructure. The greatest gains in well-being in urban areas can be achieved by prioritising access to finance to reduce climate risk for low-income and marginalised communities including people living in informal settlements. (*high confidence*) {*4.4*, *4.5.3*, *4.5.5*, *4.5.6*}

C.5.4 The design of regulatory instruments and economic instruments and consumption-based approaches, can advance equity. Individuals with high socio-economic status contribute disproportionately to emissions, and have the highest potential for emissions reductions. Many options are available for reducing emission-intensive consumption while improving societal well-being. Socio-cultural options, behaviour and lifestyle changes supported by policies, infrastructure, and technology can help end-users shift to low-emissions-intensive consumption, with multiple co-benefits. A substantial share of the population in low-emitting countries lack access to modern energy services. Technology development, transfer, capacity building and financing can support developing countries / regions leapfrogging or transitioning to low-emissions transport systems thereby providing multiple co-benefits. Climate resilient development is advanced when actors work in equitable, just and inclusive ways to reconcile divergent interests, values and worldviews, toward equitable and just outcomes. (*high confidence*) {*2.1*, *4.4*}

Governance and Policies

C.6 Effective climate action is enabled by political commitment, well-aligned multilevel governance, institutional frameworks, laws, policies and strategies and enhanced access to finance and technology. Clear goals, coordination across multiple policy domains, and inclusive governance processes facilitate effective climate action. Regulatory and economic instruments can support deep emissions reductions and climate resilience if scaled up and applied widely. Climate resilient development benefits from drawing on diverse knowledge. (*high confidence*) {*2.2, 4.4, 4.5, 4.7*}

C.6.1 Effective climate governance enables mitigation and adaptation. Effective governance provides overall direction on setting targets and priorities and mainstreaming climate action across policy domains and levels, based on national circumstances and in the context of international cooperation. It enhances monitoring and evaluation and regulatory certainty, prioritising inclusive, transparent and equitable decision-making, and improves access to finance and technology (see C.7). (*high confidence*) {*2.2.2, 4.7*}

C.6.2 Effective local, municipal, national and subnational institutions build consensus for climate action among diverse interests, enable coordination and inform strategy setting but require adequate institutional capacity. Policy support is influenced by actors in civil society, including businesses, youth, women, labour, media, Indigenous Peoples, and local communities. Effectiveness is enhanced by political commitment and partnerships between different groups in society. (*high confidence*) {*2.2, 4.7*}

C.6.3 Effective multilevel governence for mitigation, adaptation, risk management, and climate resilient development is enabled by inclusive decision processes that prioritise equity and justice in planning and implementation, allocation of appropriate resources, institutional review, and monitoring and evaluation. Vulnerabilities and climate risks are often reduced through carefully designed and implemented laws, policies, participatory processes, and interventions that address context specific inequities such as those based on gender, ethnicity, disability, age, location and income. (*high confidence*) {*4.4, 4.7*}

C.6.4 Regulatory and economic instruments could support deep emissions reductions if scaled up and applied more widely (*high confidence*). Scaling up and enhancing the use of regulatory instruments can improve mitigation outcomes in sectoral applications, consistent with national circumstances (*high confidence*). Where implemented, carbon pricing instruments have incentivized low-cost emissions reduction measures but have been less effective, on their own and at prevailing prices during the assessment period, to promote higher-cost measures necessary for further reductions (*medium confidence*). Equity and distributional impacts of such carbon pricing instruments, e.g., carbon taxes and emissions trading, can be addressed by using revenue to support low-income households, among other approaches. Removing fossil fuel subsidies would reduce emissions[54] and yield benefits such as improved public revenue, macroeconomic and sustainability performance; subsidy removal can have adverse distributional impacts, especially on the most economically vulnerable groups which, in some cases can be mitigated by measures such as redistributing revenue saved, all of which depend on national circumstances (*high confidence*). Economy-wide policy packages, such as public spending commitments and pricing reforms, can meet short-term economic goals while reducing emissions and shifting development pathways towards sustainability (*medium confidence*). Effective policy packages would be comprehensive, consistent, balanced across objectives, and tailored to national circumstances (*high confidence*). {*2.2.2, 4.7*}

C.6.5 Drawing on diverse knowledges and cultural values, meaningful participation and inclusive engagement processes—including Indigenous Knowledge, local knowledge, and scientific knowledge—facilitates climate resilient development, builds capacity and allows locally appropriate and socially acceptable solutions. (*high confidence*) {*4.4, 4.5.6, 4.7*}

[54] Fossil fuel subsidy removal is projected by various studies to reduce global CO_2 emission by 1 to 4%, and GHG emissions by up to 10% by 2030, varying across regions (*medium confidence*).

Finance, Technology and International Cooperation

C.7 Finance, technology and international cooperation are critical enablers for accelerated climate action. If climate goals are to be achieved, both adaptation and mitigation financing would need to increase many-fold. There is sufficient global capital to close the global investment gaps but there are barriers to redirect capital to climate action. Enhancing technology innovation systems is key to accelerate the widespread adoption of technologies and practices. Enhancing international cooperation is possible through multiple channels. (*high confidence*) {*2.3, 4.8*}

C.7.1 Improved availability of and access to finance[55] would enable accelerated climate action (*very high confidence*). Addressing needs and gaps and broadening equitable access to domestic and international finance, when combined with other supportive actions, can act as a catalyst for accelerating adaptation and mitigation, and enabling climate resilient development (*high confidence*). If climate goals are to be achieved, and to address rising risks and accelerate investments in emissions reductions, both adaptation and mitigation finance would need to increase many-fold (*high confidence*). {*4.8.1*}

C.7.2 Increased access to finance can build capacity and address soft limits to adaptation and avert rising risks, especially for developing countries, vulnerable groups, regions and sectors (*high confidence*). Public finance is an important enabler of adaptation and mitigation, and can also leverage private finance (*high confidence*). Average annual modelled mitigation investment requirements for 2020 to 2030 in scenarios that limit warming to 2°C or 1.5°C are a factor of three to six greater than current levels[56], and total mitigation investments (public, private, domestic and international) would need to increase across all sectors and regions (*medium confidence*). Even if extensive global mitigation efforts are implemented, there will be a need for financial, technical, and human resources for adaptation (*high confidence*). {*4.3, 4.8.1*}

C.7.3 There is sufficient global capital and liquidity to close global investment gaps, given the size of the global financial system, but there are barriers to redirect capital to climate action both within and outside the global financial sector and in the context of economic vulnerabilities and indebtedness facing developing countries. Reducing financing barriers for scaling up financial flows would require clear signalling and support by governments, including a stronger alignment of public finances in order to lower real and perceived regulatory, cost and market barriers and risks and improving the risk-return profile of investments. At the same time, depending on national contexts, financial actors, including investors, financial intermediaries, central banks and financial regulators can shift the systemic underpricing of climate-related risks, and reduce sectoral and regional mismatches between available capital and investment needs. (*high confidence*) {*4.8.1*}

C.7.4 Tracked financial flows fall short of the levels needed for adaptation and to achieve mitigation goals across all sectors and regions. These gaps create many opportunities and the challenge of closing gaps is largest in developing countries. Accelerated financial support for developing countries from developed countries and other sources is a critical enabler to enhance adaptation and mitigation actions and address inequities in access to finance, including its costs, terms and conditions, and economic vulnerability to climate change for developing countries. Scaled-up public grants for mitigation and adaptation funding for vulnerable regions, especially in Sub-Saharan Africa, would be cost-effective and have high social returns in terms of access to basic energy. Options for scaling up mitigation in developing countries include: increased levels of public finance and publicly mobilised private finance flows from developed to developing countries in the context of the USD 100 billion-a-year goal; increased use of public guarantees to reduce risks and leverage private flows at lower cost; local capital markets development; and building greater trust in international cooperation processes. A coordinated effort to make the post-pandemic recovery sustainable over the longer-term can accelerate climate action, including in developing regions and countries facing high debt costs, debt distress and macroeconomic uncertainty. (*high confidence*) {*4.8.1*}

C.7.5 Enhancing technology innovation systems can provide opportunities to lower emissions growth, create social and environmental co-benefits, and achieve other SDGs. Policy packages tailored to national contexts and technological characteristics have been effective in supporting low-emission innovation and technology diffusion. Public policies can

[55] Finance originates from diverse sources: public or private, local, national or international, bilateral or multilateral, and alternative sources. It can take the form of grants, technical assistance, loans (concessional and non-concessional), bonds, equity, risk insurance and financial guarantees (of different types).

[56] These estimates rely on scenario assumptions.

support training and R&D, complemented by both regulatory and market-based instruments that create incentives and market opportunities. Technological innovation can have trade-offs such as new and greater environmental impacts, social inequalities, overdependence on foreign knowledge and providers, distributional impacts and rebound effects[57], requiring appropriate governance and policies to enhance potential and reduce trade-offs. Innovation and adoption of low-emission technologies lags in most developing countries, particularly least developed ones, due in part to weaker enabling conditions, including limited finance, technology development and transfer, and capacity building. (*high confidence*) {*4.8.3*}

C.7.6 International cooperation is a critical enabler for achieving ambitious climate change mitigation, adaptation, and climate resilient development (*high confidence*). Climate resilient development is enabled by increased international cooperation including mobilising and enhancing access to finance, particularly for developing countries, vulnerable regions, sectors and groups and aligning finance flows for climate action to be consistent with ambition levels and funding needs (*high confidence*). Enhancing international cooperation on finance, technology and capacity building can enable greater ambition and can act as a catalyst for accelerating mitigation and adaptation, and shifting development pathways towards sustainability (*high confidence*). This includes support to NDCs and accelerating technology development and deployment (*high confidence*). Transnational partnerships can stimulate policy development, technology diffusion, adaptation and mitigation, though uncertainties remain over their costs, feasibility and effectiveness (*medium confidence*). International environmental and sectoral agreements, institutions and initiatives are helping, and in some cases may help, to stimulate low GHG emissions investments and reduce emissions (*medium confidence*). {*2.2.2, 4.8.2*}

[57] Leading to lower net emission reductions or even emission increases.

The Greenhouse Gas Footprint of Liquefied Natural Gas (LNG) Exported from the United States

Robert W. Howarth

Department of Ecology & Evolutionary Biology, Cornell University, Ithaca, NY 14853 USA

Keywords: methane, methane emissions, fugitive emissions, methane slippage, boil off, LNG tanker, liquefaction, lifecycle analysis, global warming potential, GWP, GWP_{20}

Abstract

Before 2016, the export of liquefied natural gas (LNG) from the United States was banned, but since that time exports have risen rapidly, fueled in part by the rapid growth in shale gas production. Today the United States is the largest exporter of LNG. This paper presents a full lifecycle assessment for greenhouse gas emissions from LNG. These emissions depend on the type of tanker used to transport the LNG, with emissions far larger when LNG is transported by older, steam-powered tankers burning heavy fuel oil. The largest source of emissions in this case is from venting of methane lost by evaporation from the storage tanks, called boil off. More modern tankers, whether powered by steam or 4-stroke or 2-stroke engines, can capture this boil-off methane and use it for their power, thereby greatly lowering methane emissions. For scenarios for LNG that is transported by more modern tankers, the single largest source of emissions in the full lifecycle are those from the production, processing, storage, and transport of the natural gas that comprises the feedstock for LNG. Fugitive emissions of unburned methane are particularly important, but so are the carbon dioxide emissions from the energy intensive processes behind modern shale gas extraction. In all of the scenarios considered, across all types of tankers used to transport LNG, methane emissions exceed emissions of carbon dioxide from the final combustion of LNG. Carbon dioxide emissions other than from this final combustion are significant, but smaller than the carbon dioxide from the final combustion. While some proponents of LNG have argued it has a climate benefit by replacing coal, the analysis presented here disproves this. Across all scenarios considered, total greenhouse gas emissions from LNG are larger than those from coal, ranging from 24% to 274% greater.

Introduction

In this paper, I analyze the greenhouse gas footprint of liquefied natural gas (LNG) produced in and exported from the United States. The United States prohibited the export of LNG before 2016, but since the lifting of the ban at that time, exports have risen rapidly (DiSavino 2017). In 2022 the United States became the largest exporter of LNG globally (EIA 2023). Exports doubled between 2019 and 2023, and they are predicted to double again over the next four years (Joselow and Puko 2023). As of 2022, the LNG exported from the United States represented almost 20% of all global LNG transport (based on US export of 104.3 billion m^3 and total global transport of 542 billion m^3; Statista 2023-a, 2023-b).

Proponents of this increase in LNG exports from the United States often claim a climate benefit, arguing that the alternative to the increased export of LNG both to Europe and Asia would be greater use of coal (Sneath 2023; Joselow and Puko 2023). In fact, even though carbon dioxide emissions are greater from burning coal than from burning natural gas, methane emissions can more than offset this difference (Howarth et al. 2011; Howarth 2014; Howarth and Jacobson 2021; Gordon et al. 2023). As a greenhouse gas, methane is more than 80 times more powerful than carbon dioxide when considered over a 20 year period (IPCC 2021), and so even small methane emissions can have a large climate impact. Clearly, greenhouse gas emissions from LNG must be larger than from the natural gas from which it is made, because of the energy needed to liquefy the gas, transport the LNG, and re-gasify it. The liquefaction process alone is highly energy intensive (Hwang et al. 2014; Pace Global 2015). A full lifecycle assessment is required to determine how much greater the full magnitude of these LNG greenhouse gas emissions are.

There are relatively few previous lifecycle assessments of greenhouse gas emissions from LNG in the peer-reviewed literature, and as far as I am aware, none since the start of export of LNG from the United States in 2016 (Tamura et al. 2001; Okamura et al. 2007; Abrahams et al. 2015). Some prior assessments did not consider upstream emissions of methane from the production and use of natural gas, and none have considered the emissions of carbon dioxide associated with the production, processing, and transport of natural gas. Most natural gas production in the United States is shale gas produced by high volume hydraulic fracturing and high-precision directional drilling, two technologies that only began to be used commercially to develop shale gas in this century (Howarth 2019, 2022-a). It is the rapid increase in shale gas production in the United States that has allowed and driven the increase in export of LNG (Joselow and Puko 2023). Shale gas production is quite energetically intensive, and the related emissions of carbon dioxide need to be considered in any full lifecycle assessment of LNG. Further, methane emissions from shale gas can be substantial. Since 2008, methane emissions from shale gas in the United States may have contributed one third of the total (and large) increase in atmospheric methane globally (Howarth 2019, 2022-a).

The types of ships used to transport LNG have been changing in recent years, and the global fleet now consists of both steam-powered tankers and tankers powered by internal-combustion engines, particularly 4-stroke engines, although increasingly 2-stroke engines are coming into play as well (Bakkali and Ziomas 2019; Pavlenko et al. 2020). Some steam-powered vessels can only burn heavy fuel oil, but other steam-powered tankers as well as all of the tankers powered by 4-stroke and 2-stroke engines can burn fuel oils or LNG. Emissions of both carbon dioxide and methane vary significantly across these different tankers and fuels. For example, older tankers that burn only heavy fuel oils are more likely to vent unburned methane to the atmosphere from LNG that evaporates from the storage tanks, a process called "boil off." More modern tankers can capture and use the LNG, and thus vent less boil-off methane (Bakkali and Ziomas 2019). Tankers powered by 4-stroke and 2-stroke engines are more efficient in their fuel use than are steam-powered tankers, and so have lower carbon dioxide emissions (Pavlenko et al. 2020). However, when they burn LNG as a fuel, some methane slips through unburned and is emitted in the exhaust gases (Pavlenko et al. 2020; Balcombe et al. 2021). These differences in emissions from tankers have not been fully explored in earlier lifecycle assessments and is a major focus of the analysis I present here. My analysis relies heavily on two recent, comprehensive assessments of the use of LNG as a marine fuel (Pavlenko et al. 2020; Balcombe et al. 2021).

Here, I present a full lifecycle assessment for the LNG system, from the production of shale gas that provides the feedstock through to combustion by the final consumer. My analysis focuses on emissions of carbon dioxide and methane and excludes other greenhouse gases such as nitrous oxide that are very minor contributors to total emissions for natural gas and LNG systems (Howarth 2020; Pavlenko et al. 2020). Included are emissions of carbon dioxide and methane at each step along the supply chain, including those associated with the production, processing, storage, and transport of the natural gas that is the feedstock for LNG (referred to as upstream and midstream emissions), emissions from the energy used to power the liquefaction of natural gas to LNG, emissions from the energy consumed in transporting the LNG by tanker, emissions from the energy used to re-gasify LNG to natural gas, and emissions from the delivery of gas to and combustion by the final consumer.

Methods

Calculations use net calorific values (also called lower heating values). Note that the use of net calorific values is standard in most countries, but the United States uses gross calorific values. Emissions expressed using net calorific values are 10% greater than when using gross calorific values (Hayhoe et al. 2002; Howarth et al. 2011; Howarth 2020). LNG and heavy fuel oils are assumed to have energy densities of 48.6 MJ/kg and 39 MJ/kg respectively (Engineering Toolbox 2023). I convert methane emissions to carbon dioxide equivalents using a 20-year Global Warming Potential (GWP_{20}) of 82.5 and a 100-year GWP_{100} of 29.8 (IPCC 2021).

Upstream plus midstream emissions:

Upstream plus midstream emissions are based on the total quantity of natural gas and other fuels consumed in the LNG endeavor. In addition to the natural gas burned by the final consumer, natural gas and LNG are consumed in the liquefaction, tanker transport, and regasification processes. The procedure for estimating quantities for each of these is presented below, and upstream plus midstream emissions are calculated from these total quantities and empirically determined emission factors. The methane emission factor for natural gas is based on a recent synthesis of data from 18 studies that used airplane flyovers of satellites to estimate emissions across the major shale gas field in the United States (Howarth 2022-a, 2022-b). The mean value from these studies weighted by the volume of gas production in each of the fields is 2.6% of natural gas production (Howarth 2022-b). This does not include methane that is emitted from gas distribution systems, which are separately considered. Methane emissions from producing fuel oil are estimated as 0.10 g CH4/MJ (Howarth et al. 2011). For indirect carbon dioxide emission, I use values developed by the State of New York, converting these to metric units and net calorific values: 12.6 g CO2/MJ for natural gas and 15.8 g CO2/MJ for fuel oil (DEC 2021, table A.1).

Liquefaction:

A substantial amount of energy is required to liquefy methane into LNG, and this energy is provided by burning natural gas. That is, natural gas is both the feed source and energy source used to produce LNG (Hwang et al. 2014). Carbon dioxide emissions from the combustion of the gas powering the plants have been measured at many facilities in Australia, the US, Brunei, Malaysia, Indonesia, Oman, and Qatar, with emissions varying from 230 to 410 g CO2/kg of LNG liquefied (Tamura et al. 2001; Okamura et al. 2007). Here, I use the mean estimate of 270 g CO2/kg LNG liquefied. This is comparable to the value used by Balcombe et al. (2021) in their lifecycle assessment and is at the very low end of emission estimates provided by Pace Global (2015) for guidance for new plants built in the United States: 260 to 370 g CO2 per kg of LNG liquefied.

In addition, carbon dioxide present in raw natural gas is emitted to the atmosphere as the methane in natural gas is liquefied. These emissions are estimated as 23 to 90 g CO_2/kg of LNG liquefied (Tamura et al. 2001; Okamura et al. 2007). Here I use a mean estimate of 57 g CO_2/kg. In addition, some natural gas is flared at liquefaction plants to maintain gas pressures for safety, with a range of measured carbon dioxide emissions from zero up to 50 g CO_2/kg of LNG, and a mean estimate of 18 g CO_2/kg (Tamura et al. 2001; Okamura et al. 2007). Further, some natural gas is vented as unburned methane at LNG liquefaction plants. For this, I use the central value of 0.35% of the LNG formed from Balcombe et al. (2021) who report a range of 0.011% to 0.63%. This corresponds to 3.5 g CO_2/kg of LNG liquified.

Some of the LNG that is liquefied is consumed in transporting and handling the LNG before it is consumed by the final consumer, as considered further below. Therefore, emissions of both methane and carbon dioxide from the liquefaction process are larger when expressed per kg of final consumption that per kg of LNG liquefied. In my analyses, this difference is estimated from the total amount of LNG that must be liquefied in order to provide a unit of LNG for final consumption.

Boil off of methane:

Leakage of heat through insulation causes some LNG to evaporate (boil off) as methane gas, and this must be removed from the tanks to maintain pressure. During loading and unloading, an estimated 0.45% of the LNG being loaded is boiled off (Hassan et al. 2009). This is generally used to power operations at the port facilities or flared to the atmosphere. For this analysis, I assume all of the boil off during loading and unloading is released as carbon dioxide emissions, with zero methane emissions. This underestimates methane emissions to some extent, but there are insufficient data available to robustly estimate these. The carbon dioxide emissions from the boil off during loading and unloading is added to the tanker carbon dioxide emissions estimated below, although this is a very small contribution to those emissions.

Boil off also occurs from tankers during transport at rates between 0.1% and 0.17% of the LNG cargo load per day (Gerldmyer et al. 2003; Hassan et al. 2009; BrightHub Engineering 2022). The ambient temperature is important, and rates of 0.1% per day are characteristic at 5^o C while 0.17% per day is characteristic at 25^o C (Hassan et al. 2009). Note that boil off occurs not only during the laden voyage transporting the LNG: some LNG is retained as ballast for the return voyage back to the LNG loading terminal, typically 5% of the gross cargo (Hassan et al. 2009). This is necessary to keep the tanks at low temperature, and the mass of methane boiled off per day during the return ballast voyage is essentially the same as during the laden voyage (Hassan et al. 2009). Boiled off methane can be used to fuel many tankers, and in fact contributes 80% of the fuel used globally by the LNG tanker fleet (IMO 2021). In this analysis, I assume that tankers only vent methane from boil off to the atmosphere when the rate of boil off exceeds the use of boil off as a fuel for the tanker (Bakkali and Ziomas 2019). However, some older tankers are not capable of burning boil off, and for these, I assume all boil off is vented to the atmosphere as unburned methane. While some modern tankers are able to reliquefy methane to LNLG, this is not common, and the necessary equipment is absent from older, steam-powered tankers (Hassan et al. 2009).

Fuel consumption rate and emissions from LNG tankers:

My analysis considers four different types of tankers: 1) steam-powered vessels that burn only heavy fuel oil; 2) steam-powered vessels that can use either fuel oil or methane from the boil off of LNG; 3) modern tankers built over the past 20 years that are powered by 4-cycle engines capable of using fuel oil, diesel oil, or methane from LNG boil off; and 4) tankers powered by 2-cycle engines capable of using either diesel oil or boil off. At one time, almost all LNG tankers were powered by steam engines that burned only heavy fuel oil, and some of these are still in operation. However, the LNG tanker fleet today is dominated by steam-powered engines that can burn LNG and 4-stroke engines (Bakkali and Ziomas 2019; Pavlenko et al. 2020). As of 2019, LNG tankers powered by 2-stroke engines were rare although at least one was in construction and another four were planned (Bakkali and Ziomas 2019; Pavlenko et all. 2020).

In this paper, I assume that any tanker that can use LNG for its fuel will meet virtually all of its fuel needs from this source. Boil off in excess of the energy needs of the tanker is assumed to be vented to the atmosphere as unburned methane. While some vessels have equipment for reliquefying methane to LNG rather than venting, this is not common, particularly on older steam-powered tankers, which typically vent boil-off methane (Hassan et al. 2009). Although most tankers can burn fuel oil and/or diesel oil, consumption of these fuels tends to be very low compared to LNG (Raza and Schoyen 2014; Bakkali and Ziomas 2019; Balcombe et al. 2022), except in those rare times when LNG prices are high relative to fuel oils (Jaganathan and Khasawneh 2021). And while it might be expected that tankers would burn fuel oil if the rate of boil off were not sufficient, many tankers instead are likely to force more boil off for their fuel, at rates greater than the 0.1% to 0.17% per day, in part to meet stringent sulfur emission standards for ships that went into effect in 2020 (Bakkalil and Ziomas 2019). Fuel consumption rates are assumed to be 175 tons LNG per day for steam-powered tankers, 130 tons LNG per day for ships powered by 4-cycle engines, and 108 tons LNG per day for ships powered by 2-cycle engines (Raza and Schoyen 2014; Bakkali and Ziomas 2019). Carbon dioxide emissions from the consumption of the LNG are taken as 2,750 g CO_2/ton of LNG (IMO 2021). Carbon dioxide emissions and fuel oil use for those steam-powered tankers that can only burn heavy fuel oils are scaled to those from LNG-powered tankers, assuming 80 g CO_2/MJ for heavy fuel oil and 55 g CO_2/MJ for LNG (Pavlenko et al. 2020).

Some unburned methane is emitted in the exhaust streams from LNG tankers, particularly from those powered by 4-stroke and 2-stroke engines fueled by LNG. For vessels powered by 4-stroke engines, I assume this methane release is 3.1% of the LNG burned by the tanker, based on data in (Balcombe et al. 2021). This emission rate is slightly lower than assumed by Pavlenko et al. (2020). For tankers powered by 2-stroke engines, I assume a 3.8% methane emission rate based on data in Balcombe et al. (2022) for a newly commissioned tanker. Note that this is higher than 2.3% reported in Balcombe et al. (2021) or values reported in Pavlenko et al. (2020), due to emissions of unburned methane from electric generators, which are necessary for tankers powered by 2-stroke engines. Methane emissions in the exhaust of steam-powered tankers is negligible and are ignored in this analysis (Pavlenko et al. 2020).

Volume of LNG cargo and length of tanker voyages:

Most LNG tankers have total capacities between 125,000 to 150,000 m^3 (Bai and Jin 2016). In this analysis, I use a value of 135,000 m^3, or 67,500 tons LNG (Raza and Schoyne 2014). Generally, not all of the gross LNG cargo is unloaded at the point of destination. Some is retained for the return voyage, both to serve as fuel and to keep the LNG tanks supercooled. Here, I assume that 90% of the cargo is unloaded (Raza and Schoyne 2014). Therefore, the average delivered cargo is 60,800 tons LNG.

For the length of the voyage, I use the global average distance for LNG tankers (16,200 km each way) as well as the shortest regular commercial route from the US (9,070 km each way, Sabine Pass, TX to the UK;) and the longest regular commercial route from the US (29,461 km each way, Sabine Pass, TX to Shanghai; Oxford Institute for Energy Studies 2018). The vast majority of LNG exports from the US are from the Sabine Pass area, so these distances well characterize US exports (Joselow and Puko 2023). Considering the average speed of 19 knots (35.2 km per hour; Oxford Institute for Energy Studies), these cruise distances correspond to times of 19 days, 10.7 days, and 35 days each way, respectively. Note that the travel distances for LNG tankers have been increasing over time (Timera Energy 2019). In 2023, a drought limited the capacity of the Panama Canal, leading to LNG tankers from Texas to Asia taking longer routes through the Suez Canal or south of Good Hope in Africa (Williams 2023).

Final distribution and combustion:

In addition to the methane emissions from upstream and midstream sources before the gas is liquefied to become LNG, considered above, emissions occur after regasification and delivery to the final customer. These emissions are less if the gas is used to generate electricity than if it is delivered to homes and buildings. For my baseline analysis, I consider electricity generation. For this, methane emissions from transmission pipelines and storage in the destination country are estimated as 0.32% of the final gas consumption (Alvarez et al. 2018).

When the gas is burned by the final consumer, I assume carbon dioxide emissions of 2,750 g CO2/ton of LNG delivered. This is based on the stoichiometry of carbon dioxide (44 g/mole) and methane (16 g/mole). It is equivalent to 55 g CO2/MJ for natural gas (Hayhoe et al. 2002) and is also the value assumed by the IMO 2021) for burning LNG in tankers.

Comparison to coal:

To compare the greenhouse gas footprint of LNG to that of coal, I use values from Howarth (2020) for carbon dioxide emitted during combustion of coal (99 g CO2/MJ) and for upstream fugitive methane emissions associated with coal (0.20 g CHk4/MJ), converted to net calorific values. For the indirect emissions of carbon dioxide from the production and transportation of coal, I use the value developed by the State of New York (3.1 g CO2/MJ), converted to metric units and net calorific values (DEC 2021, Table A-1).

Results and Discussion

The rate of LNG used to power tankers is compared with unforced boil off in Table 1, for those tankers that are capable of burning LNG. The unforced boil off predicted from the assumed percentage of gross cargo per day, 0.1% at an ambient temperature of 5° C and 0.17% at a temperature of 25° C (Hassan et al. 2009), is always less than the fuel required for tankers powered by steam engines and 4-stroke engines. This is also true for tankers powered by 2-stroke engines at the lower temperature. My analysis therefore assumes that these tankers force additional boil off to meet their fuel needs (Bakkali and Ziomas 2019), and the total LNG fuel consumption is included in the overall lifecycle assessment for each type of tanker. For tankers powered by 2-stroke engines at the higher temperature, the unforced boil off of 115 tons LNG per day exceed the fuel requirement of 108 tons LNG per day, although not by much (Table 1). All tankers powered by 2-stroke engines are relatively new and are likely to be equipped with equipment to re-liquefy boil off in excess of their fuel needs. Consequently, I assume that no boil off from these tankers is vented to the atmosphere and all is captured. However, steam-powered tankers that cannot use LNG for fuel are older and are extremely unlikely to have the re-liquefaction equipment, so their boil-off methane is assumed to be vented to the atmosphere (Hassan et al. 2009).

Table 2 presents emissions of carbon dioxide, methane, and total combined emissions expressed as CO_2-equivalents for each of the four scenarios considered, using different types of tankers and the global average time for voyages. Emissions are separated into the upstream plus midstream emissions, those from liquefaction of gas into LNG, emissions from the tankers (including from loading and unloading), emissions associated with the final transmission to consumers, and emissions as the gas is burned by the final consumer. These emissions are also summarized in Figure 1, with emissions broken down into the carbon dioxide emitted as the fuel is burned by the final consumer, other carbon dioxide emissions, and emissions of unburned methane. For both Figure 1 and the combined emissions presented in Table 2, methane emissions are compared to carbon dioxide using GWP_{20} (IPCC 2021). The emissions for the scenario using tankers powered by steam engines burning heavy fuel oil are far larger than for the other three scenarios. This is largely due to the venting to the atmosphere of unburned methane from boil. This venting contributes 36% of the total greenhouse gas emissions for the scenario based on these steam-powered tankers using heavy fuel oil (Table 2).

Carbon dioxide emissions from final combustion are important but not a dominant part of total greenhouse gas emissions across all four scenarios. These final-combustion emissions make 23% of total greenhouse gas emissions (expressed as carbon dioxide equivalents) and up 63% of total carbon dioxide emissions (not including methane) for the case where LNG is transported by steam-powered tankers using heavy fuel oil. For the other three scenarios where tankers burn LNG rather than heavy fuel oil, the emissions from final combustion make up approximately 37% of total greenhouse gas emissions and 67% of all carbon dioxide emissions (Figure 1, Table 2). Even larger than the carbon dioxide emissions from combustion of the LNG by the final customer, though, are upstream and midstream emissions from producing, processing, storing, and transporting natural gas (Table 2). This is true across all scenarios, with these emissions composing 29% of total emissions for the scenario where tankers burn heavy fuel oil and approximately 44% of total emissions in the other three scenarios. Indirect carbon dioxide emissions are an important part of these upstream and midstream emissions, reflecting the use of fossil fuels to power the natural gas extraction and processing systems, but methane emissions from upstream and midstream sources are several times higher across all scenarios (Table 2).

The liquefaction process is an important source of emissions of both carbon dioxide and methane, with methane emissions being somewhat larger (when expressed as carbon dioxide equivalents; Table 2). These liquefaction emissions are the second largest source of emissions, after the upstream and midstream emissions, for all three scenarios where LNG is transported by tankers that burn LNG, although these are dwarfed by boil off methane emissions from tankers for the scenario where the tankers are powered by heavy fuel oil. Tanker emissions dominate for this scenario of LNG being transported by steam-engine tankers that burn heavy fuel oil, but emissions from tankers are relatively small in the other scenarios (Table 2). Of interest, among the tankers that burn LNG, carbon dioxide emissions are greatest for those powered by steam engines, with lower emissions from vessels powered by more modern 4-stroke and 2-stroke engines (Table 2), reflecting greater efficiencies (Table 1). However, methane emissions, which are negligible in the tankers powered by steam engines, are significant in tankers with 4-stroke and 2-stroke engines, with these emissions (expressed as carbon-dioxide equivalents) being larger than carbon dioxide emissions from the exhaust of these vessels (Table 2). These methane emissions result from slippage of methane, that is methane emitted unburned in the exhaust stream (Pavlenko et al. 2020; Balcombe et al. 2021, 2022). As noted above, my analysis assumes no methane emissions from boil off in these tankers.

Methane emissions from the final transmission of gas to the consumer are relatively small, 3.5% or less of total lifecycle greenhouse gas emissions across all of the different tanker scenarios (Table 2). This is because my analysis focuses on the use of LNG to produce electricity, and the transmission pipelines that deliver gas to such facilities generally have moderately low emissions (Alvarez et al. 2018). However, LNG is also used to feed gas into urban pipeline distribution systems for use to heat homes and commercial buildings. Methane emissions for these downstream distribution systems can be quite high, with the best studies in the United States finding that 1.7% to 3.5% of the gas delivered to customers leaks to the atmosphere unburned (see summary in Howarth 2022-b). This corresponds to a range of 1,400 to 2,890 g CO_2-equivalents per kg LNG burned, increasing the total greenhouse gas footprint of LNG by up to 38% above the values shown in Table 1. Emissions from distribution systems are not as well characterized in either Europe or Asia as in the United States (Howarth 2022-b), although one study suggests emissions in Paris, France are in the middle range of those observed in the United States (Defratyka et al. 2021).

My analysis includes scenarios with the shortest and longest cruise distances from the United States, in addition to the world-average distance shown in Figure 1 and Table 2. See Supplemental Tables A and B for emission estimates from these shortest and longest voyages. The shortest distance represents a voyage from the Gulf of Mexico loading port to the United Kingdom, while the longest distance is for a voyage from the Gulf of Mexico to Shanghai, China, not going through the Panama Canal. Not surprisingly, total emissions go down for the shorter voyage and increase for the longest voyage for all four scenarios considered. This is particularly true for the scenario where LNG is transported in steam-powered tankers than burn heavy fuel oil, and is due primarily to differences in methane emissions from boil off, which is a function of time at sea (Supplemental Table A, Supplemental Table B). For all four scenarios, emissions from fuel consumption increase or decrease as travel distances and time at sea increase or decrease. The upstream and downstream emissions and emissions from liquefaction also increase or decrease as the travel distances change, when expressed per mass of

LNG delivered to the final consumer. This reflects an increase or decrease in the total amount of LNG burned or boiled off by tankers during their voyages. Qualitatively, the patterns described above based on world average tanker travel distances (Table 1) hold across the cases for shorter and longer voyages.

Figure 2 compares the greenhouse gas footprint of LNG in different tanker-delivery scenarios to those of coal and natural gas that is not liquefied, using global average tanker voyage distances and GWP_{20} for comparing methane to carbon dioxide. Coal and natural gas have very similar footprints, as we have previously demonstrated (Howarth and Jacobson 2021), indicating that natural gas does not have an inherent climate advantage over coal (Gordon et al. 2023). The footprint for LNG is greater than that of either coal or natural gas even in the case of short cruises using tankers that are powered by LNG, where the LNG emissions are 24% larger than for coal. The LNG footprint is 2.7 times greater than that of coal for the case of long cruises powered by those older tankers that burn heavy fuel oil (Figure 2).

My analysis is sensitive to the global warming potential that is used, as seen in the on-line only Supplemental Figures A and B. Using GWP_{100} instead of GWP_{20}, as was used in Figures 1 and 2, decreases the methane emissions expressed as carbon-dioxide equivalents by a factor of 2.77. While methane emissions are larger than direct or indirect carbon dioxide emissions when considered through the GWP_{20} lens for all four scenarios (Figure 1), the direct emissions of carbon dioxide from the final combustion of LNG are larger than methane emissions across three of the scenarios and equal to them in one when using GWP_{100} (Supplemental Figure A). Similarly, the greenhouse gas footprint of LNG and natural gas relative to coal decreases when viewed through the lens of GWP_{100} (Supplemental Figure B; Figure 2) since methane emissions from coal are less than from natural gas and LNG. Even so, greenhouse gas emissions from LNG are at least as much as from coal, in the scenario with short voyages and tankers burning LNG, to considerably worse than coal, for the scenario of long voyages by tankers burning heavy fuel oil (Supplemental Figure B). Even when using GWP100, LNG is never preferable to coal from the standpoint of greenhouse gas emissions.

While the 100-year time frame of GWP_{100} is widely used in lifecycle assessments and greenhouse gas inventories, it understates the extent of global warming that is caused by methane, particularly on the time frame of the next several decades. The use of GWP_{100} dates back to the Kyoto Protocol in the 1990s, and was an arbitrary choice made at a time when few were paying much attention to the role of methane as an agent of global warming. As the Intergovernmental Panel on Climate Change stated in their AR5 synthesis report, "there is no scientific argument for selecting 100 years compared with other choices" (IPCC 2013). The latest IPCC AR6 synthesis reports that methane has contributed 0.5^{o} C of the total global warming to date since the late 1800s, compared to 0.75^{o} C for carbon dioxide (IPCC 2021). And the rate of global warming over the next few decades is critical, with the rate of warming important in the context of potential tipping points in the climate system (Ritchie et al. 2023). Reducing methane emissions rapidly is increasingly viewed as critical to reaching climate targets (Collins et al. 2018; Nzotungicimpaye et al. 2023). In this context, many researchers call for using the 20-year time frame of GWP_{20} instead of or in addition to GWP_{100} (Howarth 2014, 2020; Ocko et al. 2017; Fesenfeld et al. 2018; Pavlenko et al. 2020; Howarth and Jacobson 2021; Balcombe et al. 2021, 2022). GWP_{20} is the preferred approach in my analysis presented in this paper. Using GWP_{20}, LNG always has a larger greenhouse gas footprint than coal.

In many ways, my analysis may be conservative and underestimate emissions from the global tanker fleet on average, since I am relying on data available from facilities and ships which have allowed researchers access. These are likely to have better operations and lower emissions than average. Balcombe et al. (2022) have argued for the urgent need to expand emissions measurements to a much larger number of tankers that are more representative of the global fleet, and for independent researchers to conduct these measurements. My analysis assumes that those tankers that are capable of burning LNG for their propulsion do so, and that boil-off methane is effectively captured and used on these tankers with zero venting of unburned methane. The reality for many tankers may be quite different, with potentially significant venting of methane, as is the case for tankers that cannot burn LNG.

My analysis leads to one strong recommendation: the venting of unburned methane from tanker boil off should be prohibited, and those older tankers that cannot capture and use boil-off methane should be retired within the near future. These older tankers that burn heavy fuel oil have a very large greenhouse gas footprint (Figure 2).

A broader conclusion is the need to move away from any use of LNG as a fuel as quickly as possible, and to immediately stop construction of any new LNG infrastructure. Those proponents of exporting LNG from the United States are wrong when they assert a climate benefit for the use of LNG over coal (Sneath 2023; Joselow and Puko 2023). In fact, the LNG greenhouse gas footprint is larger than that of coal (Figure 2), and short-term energy needs such as those caused by the Russian invasion of Ukraine are better met by reopening closed coal facilities, on a temporary basis, than by expanding LNG infrastructure. Any new LNG infrastructure will become a stranded asset as society moves away from all fossil fuels. In recent years, many have recognized that we need to move away from natural gas, as well as coal, to address the climate emergency (Gaventa and Patukhova 2021; Figueres 2021). With an even greater greenhouse gas footprint than natural gas, ending the use of LNG must be a global priority.

Acknowledgements
I thank Roxanne Marino for valuable discussions leading to this manuscript. This work was supported by a grant from the Park Foundation and by an endowment given by David R. Atkinson to support the professorship at Cornell University held by Robert W. Howarth.

Disclosure statement
The author confirms that he has no conflicts of interest that would adversely influence this research. The research was supported by a grant from the Park Foundation and by an endowment given by David R. Atkinson to support the professorship at Cornell University held by Robert W. Howarth.

Data availability
All data used in this paper are from publicly available sources that are identified in the manuscript.

ORCID
Robert W. Howarth http://orcid.org/0000-0001-9531-4288

Figure legends

Figure 1. Full lifecycle greenhouse gas footprints for LNG expressed per mass of LNG burned by final consumer, comparing four scenarios where the LNG is transported by different types of tankers. Emissions of methane, the carbon dioxide emitted from the final combustion, and other carbon dioxide emissions are shown separately. Methane emissions are converted to carbon dioxide equivalents using GWP_{20}. See text.

Figure 2. Full lifecycle greenhouse gas footprint for coal and natural gas compared to four scenarios where LNG is transported by tankers that either burn LNG or heavy fuel oil for long or short voyages. Methane emissions are converted to carbon dioxide equivalents using GWP_{20}. See text.

Supplemental Figure A. Full lifecycle greenhouse gas footprints for LNG expressed per mass of LNG burned by final consumer, comparing four scenarios where the LNG is transported by different types of tankers. Emissions of methane, the carbon dioxide emitted from the final combustion, and other carbon dioxide emissions are shown separately. Methane emissions are converted to carbon dioxide equivalents using GWP_{100}. See text.

Supplemental Figure B. Full lifecycle greenhouse gas footprint for coal and natural gas compared to four scenarios where LNG is transported by tankers that either burn LNG or heavy fuel oil for long or short voyages. Methane emissions are converted to carbon dioxide equivalents using GWP_{100}. See text.

References:

Abrahams L, Samaras C, Griffin W, Matthews H. 2015. Life cycle greenhouse gas emissions from U.S. liquefied natural gas exports: implications for end uses. Environmental Science & Technology 49:3237-3245. doi:10.1021/es505617p

Alvarez R, Zavalao-Araiza D, Lyon D, Allen D, Barkley Z, Brandt A, Davis K, Herndon S, Jacob D, Karion A, et al. 2018. Assessment of methane emissions from the U.S. oil and gas supply chain. Science. 361:186–188. doi:10.1126/science.aar7204

Bakkali N, Ziomas L. 2019. Forced boil off of gas: the future of LNG as a fuel for LNG carriers. McKinsey. [accessed Sept 10, 2023] https://www.mckinsey.com/industries/oil-and-gas/our-insights/forced-boil-off-gas-the-future-of-lng-as-a-fuel-for-lng-carriers

Balcombe P, Staffel I, Kerdan I, Speirs J, Brandon N, Hawkes A. 2021. How can LNG-fuelled ships meet decarbonisation targets? An environmental and economic analysis. Energy. 227: 120462. doi:10.1016/j.energy.2021.120462

Balcombe P, Heggo D, Harrison M. 2022. Total methane and CO2 emissions from liquified natural gas carrier ships: The first primary measurements. Environmental Science & Technology. 56:9632-9640. doi:10.1021/acs.est.2c01383

BrightHub Engineering. 2022. Dual-fuel engines in LNG tankers. BrightHub Engineering [accessed Oct 12, 2023] https://www.brighthubengineering.com/naval-architecture/111619-propulsion-methods-for-modern-lng-tankers/

Collins WJ, Webber CP, Cox PM, Huntingford C, Lowe J, Sitch S, Chadburn SE, Comyn-Platt E, Harper AB, Hayman G, Powell T. 2018. Increased importance of methane reduction for a 1.5 degree target. Environmental Research Letters. 13:054003. doi:10.1088/1748-9326/aab89c

DEC. 2021. Statewide greenhouse gas emissions report. New York State Department of Environmental Conservation. [accessed Oct 16, 2023]. https://www.dec.ny.gov/energy/99223.html#Report

Defratyka S, Paris J, Yver-Kwok C, Fernandez J, Korben P, Bousquet P. 2021. Mapping urban methane sources in Paris, France. Environmental Science and Technology 55:8583–8591. doi:10.1021/acs.est.1c00859

DiSavino S. 2017. After six decades, US set to turn natgas exporter amid LNG boom. Reuters. [access Oct 16, 2023]. https://www.reuters.com/article/us-usa-natgas-lng-analysis/after-six-decades-u-s-set-to-turn-natgas-exporter-amid-lng-boom-idUSKBN1700F1

EIA. 2023. The United States became the world's largest LNG exporter in the first half of 2022. Energy Information Agency, US Department of Energy. July 25, 2023. [accessed Oct 17, 2023]. https://www.eia.gov/todayinenergy/detail.php?id=53159

Engineering ToolBox. 2003. Fuels - higher and lower calorific values. EngineeringToolBox.com. (accessed Oct 9, 2023] https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

EPA. 1996. Methane emissions from the natural gas industry, Volume 6: Vented and combustion source summary. U.S. Environmental Protection Agency National Risk Management Research Laboratory. June 1996. EPA - 600/R-96-080f. [accessed Oct 16, 2023]. https://www.epa.gov/sites/production/files/2016-08/documents/6_vented.pdf

Fesenfeld LP, Schmidt TS, Schrode A. 2018. Climate policy for short- and long-lived pollutants. Nature Climate Change. 8:933–936. doi:10.1038/s41558-018-0328-1

Figueres C. 2021. Gas, like coal, has no future as the world wakes up to climate emergency.

South China Morning Post. August 29, 2021. [accessed August 9, 2023]. https://www.scmp.com/comment/opinion/article/3146479/gas-coal-has-no-future-world-wakes-climate-emergency

Gaventa J, Pastukhova M. 2021. Gas under pressure as IEA launches net-zero pathway. Energy Monitor May 18, 2021. [accessed August 9, 2023]. https://energymonitor.ai/policy/net-zero-policy/gas-under-pressure-as-iea-launches-net-zero-pathway

Gordon D, Reuland F, Jacob D, Worden J, Shindell D, Dyson M. 2023. Evaluating net life-cycle greenhouse gas emissions intensities from gas and coal at varying methane leakage rates. Environmental Research Letters. 18:084008. doi:10.1088/1748-9326/ace3db

Hassan M, Zheng A, Karilmi I. 2009. Minimizing boil-off losses in liquefied natural gas transportation. Ind. Engineering Chemical Research. 48:9571–9580. doi: 10.1021/ie801975q

Hayhoe K, Kheshgi H, Jain A, Wuebbles D. 2002. Substitution of natural gas for coal: climatic effects of utility sector emissions. Climatic Change. 54:107–139.

Howarth RW. 2014. A bridge to nowhere: Methane emissions and the greenhouse gas footprint of natural gas. Energy Science & Engineering. 2:47-60. doi:10.1002/ese3.35

Howarth R. 2019. Ideas and perspectives: is shale gas a major driver of recent increase in global atmospheric methane? Biogeosciences. 16:3033–3046. doi:10.5194/bg-16-3033-2019.

Howarth R. 2020. Methane emissions from fossil fuels: Exploring recent changes in greenhouse-gas reporting requirements for the State of New York. Journal of Integrative Environmental Sciences. 17: 69-81. doi:10.1080/1943815X.2020.1789666.

Howarth R. 2022-a. Methane and climate change. In: John F. Stolz, W. Michael Griffin, and Daniel J. Bain (editors), Environmental Impacts from Development of Unconventional Oil and Gas Reserves, Cambridge University Press.

Howarth R. 2022-b. Methane emissions from the production and use of natural gas. EM Magazine. December 2022, pages 11-16. [accessed Oct 16, 2023]. https://www.research.howarthlab.org/documents/Howarth2022_EM_Magazine_methane.pdf

Howarth R, Santoro R, Ingraffea A. 2011. Methane and the greenhouse gas footprint of natural gas from shale formations. Climatic Change Letters. 106:679–690. doi:10.1007/s10584-011-0061-5

Howarth R, Jacobson M. 2021. How green is blue hydrogen? Energy Science and Engineering. 9:1676-1687. doi: 10.1002/ese3.956

Hwang Y, Al-AbulKarem A, Mortazavi A, Radermacher R. 2014. Pages 229-257, Chapter 5 - Natural Gas Liquefaction Cycle Enhancements and Optimization, Handbook of Liquefied Natural Gas. Mokhatab S, Mak J, Valappil J, Wood D (eds.). Elsevier. doi:10.1016/B978-0-12-404585-9.00005-2

IMO. 2021. Energy efficiency of ships. MEPC 77/6/1. Marine Environmental Protection Committee, International Maritime Organization. [accessed Sept 10, 2023] https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC%2077-6-1%20-%202020%20report%20of%20fuel%20oil%20consumption%20data%20submitted%20to%20the%20IMO%20Ship%20Fuel%20Oil%20Consumption%20Database%20in%20GISIS.pdf

IPCC. 2013. Climate change 2013. The physical science basis. Contribution of working group i to the fifth assessment report of the intergovernmental panel on climate change, change. [accessed August 9, 2023]. https://www.ipcc.ch/report/ar5/wg1/

IPCC. 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte V, Zhai P, Pirani A, Connors S, Péan C, Berger S, Caud N, Chen Y, Goldfarb L, Gomis M, Huang M, Leitzell K, Lonnoy E, Matthews J, Maycock T, Waterfield T, Yelekçi O, Yu R, Zhou B (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896

Jaganathan J, Khasawneh R. 2021. Update 1-Off the boil: LNG tankers burn more oil as gas prices soar. Reuters, Utilities – Natural Gas. [accessed Oct 16, 2023]. https://www.reuters.com/article/global-tankers-lng/update-1-off-the-boil-lng-tankers-burn-more-oil-as-gas-prices-soar-idUSL1N2Q50U0

Joselow M, Puko T. 2023. The next front in the climate fight: U.S. exports of natural gas. Washington Post. Oct 17, 2023. [accessed Oct 17, 2023]. https://www.washingtonpost.com/climate-environment/2023/10/17/natural-gas-exports-climate-activists/?utm_source=newsletter&utm_medium=email&utm_campaign=wp_climate202&wpisrc=nl_climate202

Nzotungicimpaye C, MacIsaac A, Zickf K. 2023. Delaying methane mitigation increases the risk of breaching the 2 °C warming limit. Communications Earth and Environment. 4:250. doi.org/10.1038/s43247-023-00898-z

Ocko IB, Hamburg SP, Jacob DJ, Keith DW, Keohane NO. 2017. Unmask temporal trade-offs in climate policy debates. Science. 356:492–493. doi:10.1126/science.aaj2350

Okamura T, Furukawa M, Ishitani H. 2007. Future forecast for life-cycle greenhouse gas emissions of LNG and city gas 13A. Applied Energy. 84:1136e49.

Oxford Institute for Energy Studies. 2018. The LNG shipping forecast: costs rebounding, outlook uncertain. Oxford Institute for Energy Studies. [accessed Oct 16, 2023]. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2018/02/The-LNG-Shipping-Forecast-costs-rebounding-outlook-uncertain-Insight-27.pdf

Pace Global. 2015. Life cycle assessment of GHG emissions from LNG and coal fired generation scenarios: assumptions and results. Pace Global. [accessed Oct 16, 2023]. https://www.ourenergypolicy.org/wp-content/uploads/2015/10/PACE_Report.pdf

Pavlenko N, Comer B., Zhou Y., Clark N. 2020. The climate implications of using LNG as a marine fuel. Working Paper 2020-02. International Council on Clean Transportation. [accessed Oct 16, 2023]. https://theicct.org/sites/default/files/publications/Climate_implications_LNG_marinefuel_01282020.pdf

Raza Z, Schoyen H. 2014. A comparative study of the northern sea route (NSR) in commercial and environmental perspective with focus on LNG shipping. 6th International conference on maritime transport, Barcelona, Spain. [accessed Oct 16, 2023]. https://www.researchgate.net/publication/272828954_A_COMPARATIVE_STUDY_OF_THE_NORTHERN_SEA_ROUTE_NSR_IN_COMMERCIAL_AND_ENVIRONMENTAL_PERSPECTIVE_WITH_FOCUS_ON_LNG_SHIPPING

Ritchie P, Alkhayuon H, Cox P, Wieczore S. 2023. Rate-induced tipping in natural and human systems. Earth Systems Dynamics. 14:669–683. doi.org/10.5194/esd-14-669-2023

Sneath S. 2023. LNG export terminals belching more pollution than estimated. The Lens. [accessed Aug 25, 2023]. https://thelensnola.org/2023/07/31/lng-export-terminals-belching-more-pollution-than-estimated/?fbclid=IwAR0zBDGWl9AGe446XX1NcWk7CXsr0DTAPHsow8Xdrn7Ai58nClchbxpsGVo

Statista. 2023-a. Leading exporting countries of liquefied natural gas worldwide in 2022. Statista Research Department. [accessed Oct 16, 2023]. https://www.statista.com/statistics/274528/major-exporting-countries-of-lng/

Statista. 2023-b. Liquefied natural gas trade volume worldwide from 1970 to 2022. Statista Research Department. [accessed Oct 16, 2023]. https://www.statista.com/statistics/264000/global-lng-trade-volume-since-1970/

Tamura I, Tanaka T, Kagajo T, Kuwabara S, Yoshioka T, Nagata T, Kurahashi K, Ishitani H. 2001. Life cycle CO2 analysis of LNG and city gas. Applied Energy 68:301-309.

Timera Energy. 2019. LNG shipping distances drive up costs. Timera Energy. [accessed Oct 16, 2023]. https://timera-energy.com/lng-shipping-distances-drive-up-costs/

Williams C. 2023. Cheniere shunning Panama Canal for longer LNG routes to Asia. Reuters. [accessed Oct 16, 2023]. https://www.reuters.com/business/energy/cheniere-shunning-panama-canal-longer-lng-routes-asia-2023-07-11/

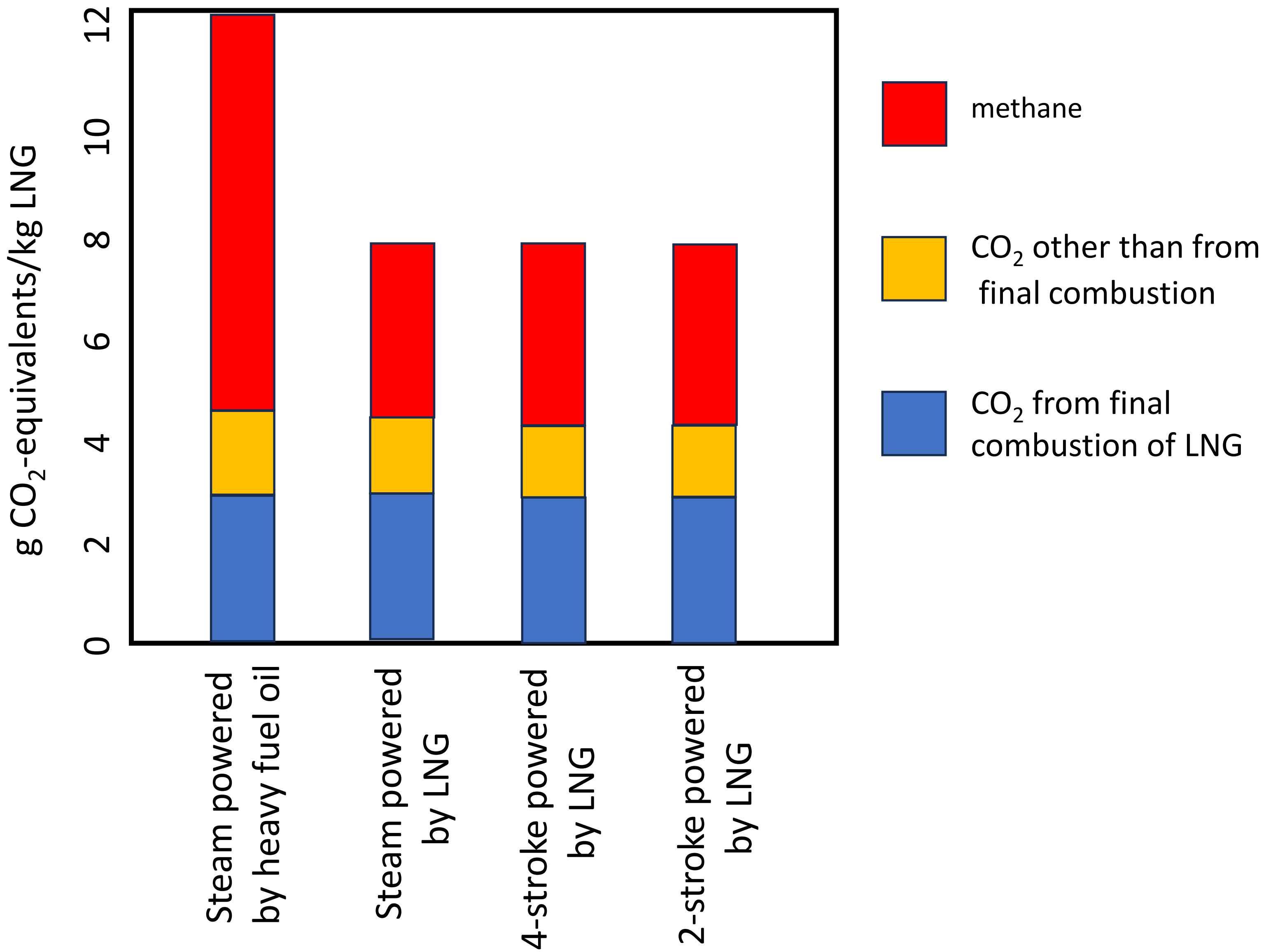
Table 1. Comparison of rate of unforced boil off and fuel needs to power different types of LNG tankers.

	Tons LNG per day
Unforced boil off, ambient temperature of 5° C	67.5 [a]
Unforced boil off, ambient temperature of 25° C	115 [a]
Steam-powered tanker burning LNG	175
Tanker powered by 4-stroke engines burning LNG	130
Tanker powered by 2-stroke engines burning LNG	108

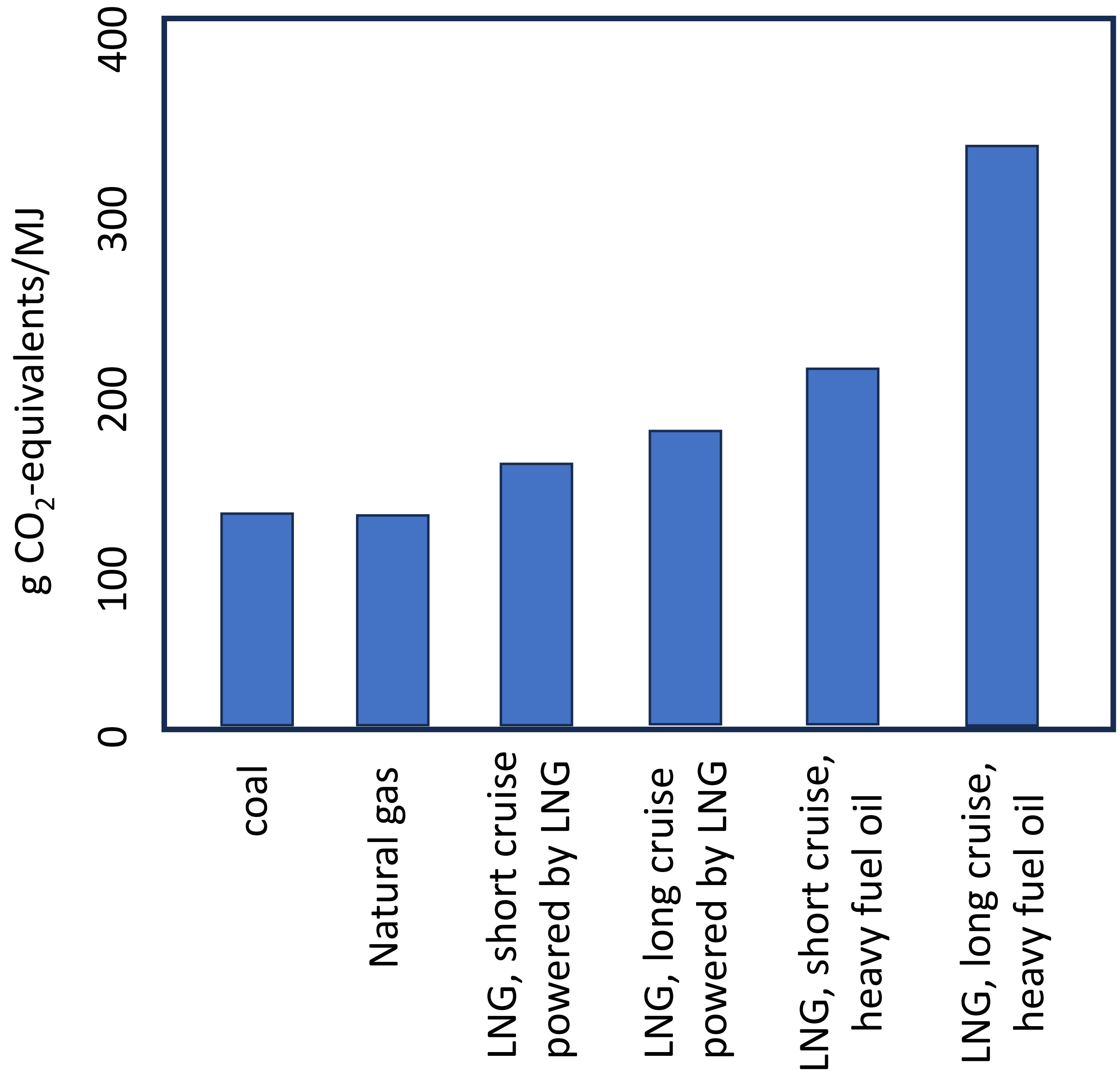
a) Assumes tanker gross cargo capacity of 67,500 tons. Unforced boil off is that which occurs due to heat leakage to LNG storage tanks. Tankers can increase boil off rate to meet fuel demand.

Table 2. Full lifecycle greenhouse gas emissions for LNG with four different scenarios for shipping by tanker, using world-average voyage times. Methane emissions are shown both as mass of methane and mass of carbon dioxide equivalents based on GWO_{20}. Values are per final mass of LNG consumed.

	Carbon Dioxide	Methane		Total combined
	g CO_2/kg	g CH_4/kg	g CO_2-eq/kg	g CO_2-eq/kg
Steam tankers powered by heavy fuel oil				
Upstream & midstream emissions	736	32.2	2,657	3,393
Liquefaction	425	4.2	347	772
Emissions from tanker	425	51.3	4,232	4,657
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,336**	**90.9**	**7,500**	**11,836**
Steam tankers powered by LNG				
Upstream & midstream emissions	718	32.5	2,681	3,399
Liquefaction	430	4.4	363	793
Emissions from tanker	300	---	---	300
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,198**	**40.1**	**3,308**	**7,506**
4-stroke engine tankers powered by LNG				
Upstream & midstream emissions	700	31.7	2,615	3,315
Liquefaction	435	4.3	355	790
Emissions from tanker	217	2.5	206	423
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,102**	**41.7**	**3,440**	**7,542**
2-stroke engine tankers powered by LNG				
Upstream & midstream emissions	691	31.3	2,582	3,273
Liquefaction	430	4.2	347	777
Emissions from tanker	179	2.6	215	394
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,050**	**41.3**	**3,408**	**7,458**



g CO_2-equivalents/kg LNG
0
2
4
6
8
10
12
Steam powered by heavy fuel oil
Steam powered by LNG
4-stroke powered by LNG
2-stroke powered by LNG
methane
CO_2 other than from final combustion
CO_2 from final combustion of LNG



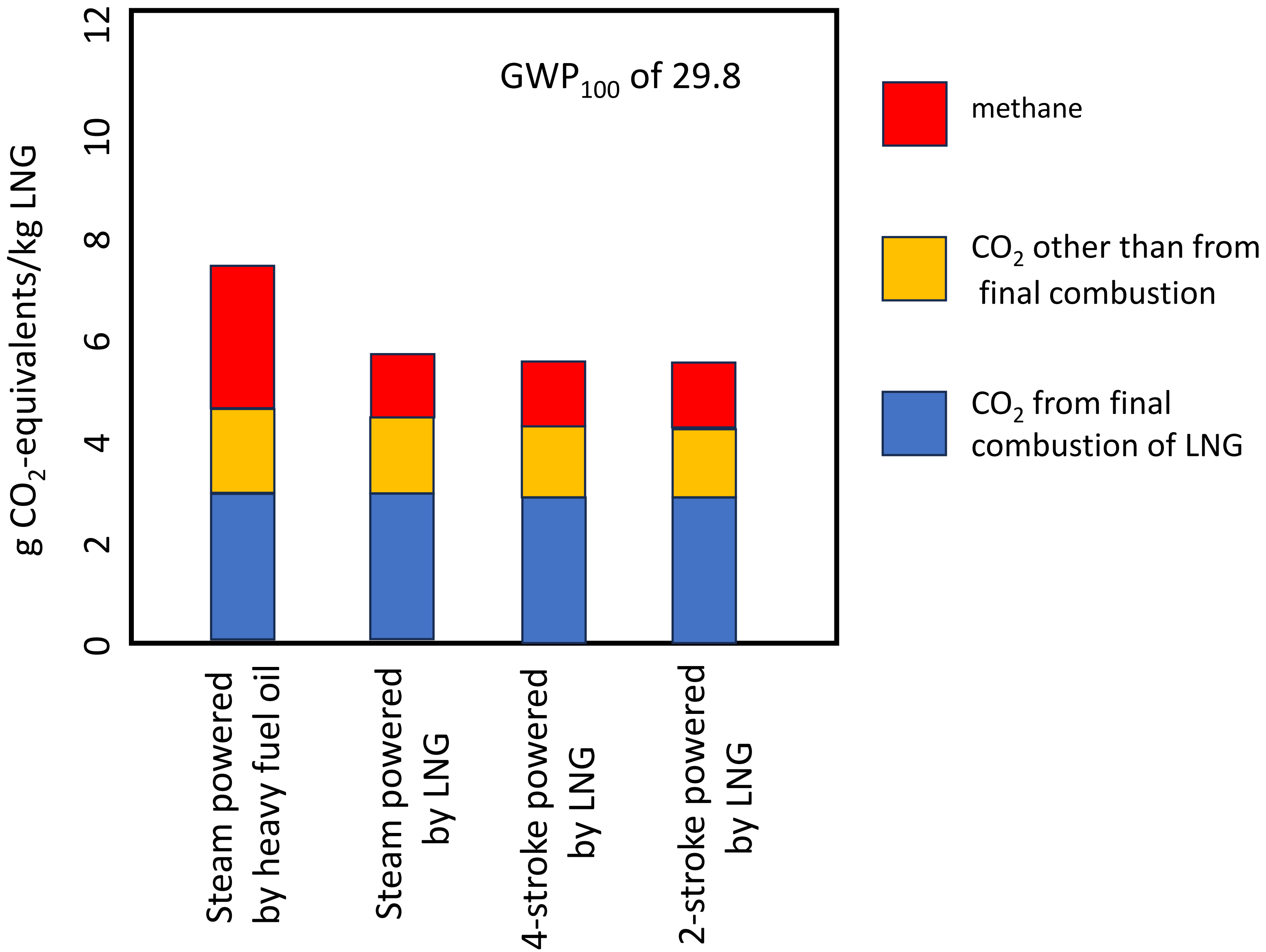
g CO_2-equivalents/MJ
0
100
200
300
400
coal
Natural gas
LNG, short cruise powered by LNG
LNG, long cruise powered by LNG
LNG, short cruise, heavy fuel oil
LNG, long cruise, heavy fuel oil

Supplemental Table A. Full lifecycle greenhouse gas emissions for LNG with four different scenarios for shipping by tanker, using shortes voyage times. Methane emissions are shown both as mass of methane and mass of carbon dioxide equivalents based on GWO_{20}. Values are per final mass of LNG consumed.

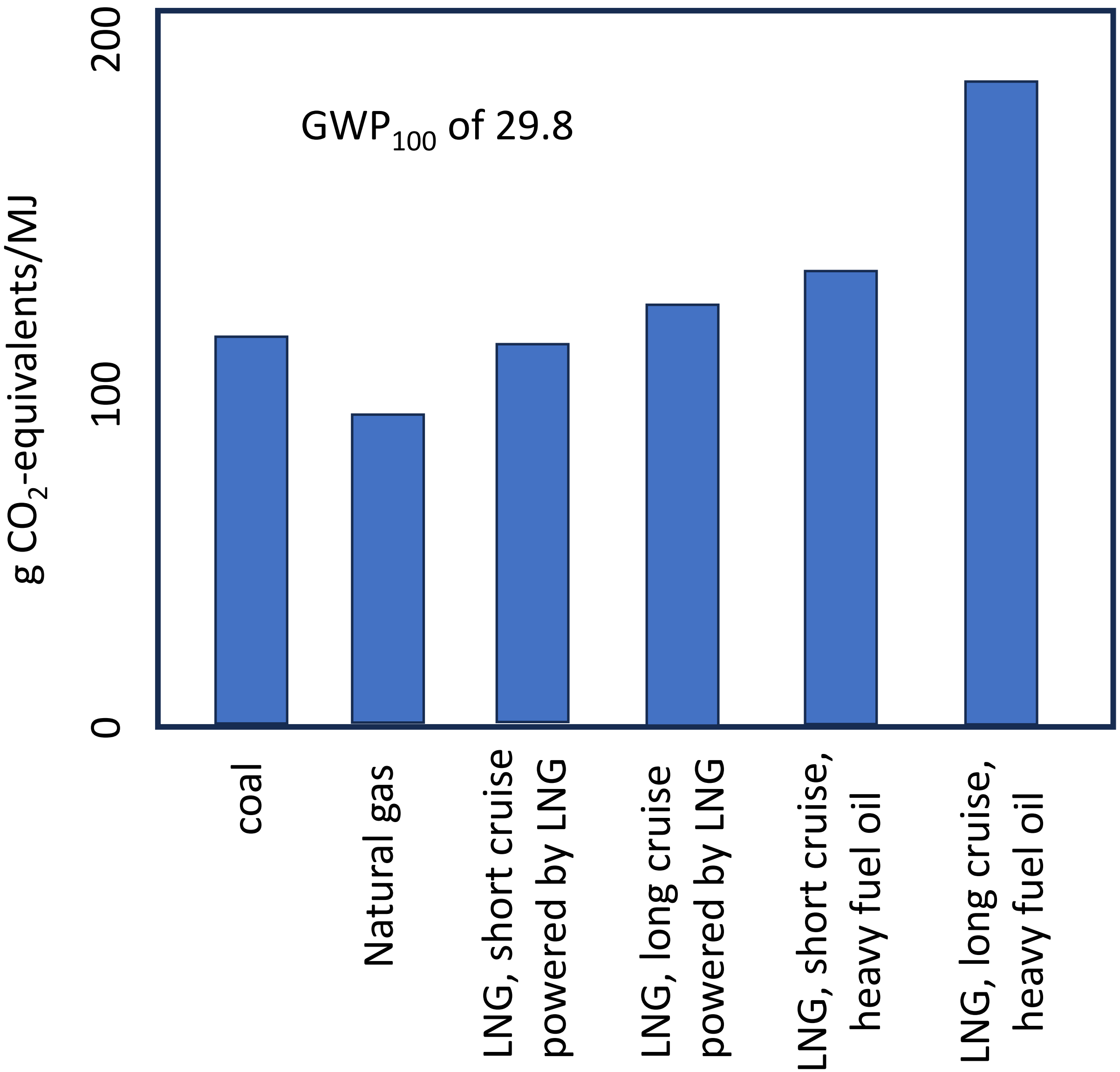
	Carbon Dioxide	Methane		Total combined
	g CO_2/kg	g CH_4/kg	g CO_2-eq/kg	g CO_2-eq/kg
Steam tankers powered by heavy fuel oil				
Upstream & midstream emissions	706	31.9	2,632	3,338
Liquefaction	414	4.1	338	752
Emissions from tanker	239	29.0	2,393	2,632
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,109**	**68.2**	**5,627**	**9,736**
Steam tankers powered by LNG				
Upstream & midstream emissions	690	31.2	2,574	3,264
Liquefaction	428	4.2	347	775
Emissions from tanker	169	---	---	169
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,037**	**38.6**	**3,185**	**7,222**
4-stroke engine tankers powered by LNG				
Upstream & midstream emissions	679	30.1	2,483	3,162
Liquefaction	422	4.1	338	760
Emissions from tanker	122	1.4	116	238
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**3,973**	**38.8**	**3,201**	**7,174**
2-stroke engine tankers powered by LNG				
Upstream & midstream emissions	674	30.0	2,475	3,149
Liquefaction	419	4.1	338	757
Emissions from tanker	101	1.4	116	217
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**3,944**	**38.7**	**3,193**	**7,137**

Supplemental Table B. Full lifecycle greenhouse gas emissions for LNG with four different scenarios for shipping by tanker, using longest voyage times. Methane emissions are shown both as mass of methane and mass of carbon dioxide equivalents based on GWO_{20}. Values are per final mass of LNG consumed.

	Carbon Dioxide	Methane		Total combined
	g CO_2/kg	g CH_4/kg	g CO_2-eq/kg	g CO_2-eq/kg
Steam tankers powered by heavy fuel oil				
Upstream & midstream emissions	745	32.7	2,698	3,443
Liquefaction	439	4.3	355	794
Emissions from tanker	783	94.5	3,347	8,579
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,717**	**134.7**	**11,113**	**15,830**
Steam tankers powered by LNG				
Upstream & midstream emissions	771	34.9	2,879	3,650
Liquefaction	478	4.7	388	866
Emissions from tanker	554	---	---	554
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,553**	**42.8**	**3,531**	**8,084**
4-stroke engine tankers powered by LNG				
Upstream & midstream emissions	739	33.4	2,756	3,495
Liquefaction	459	4.5	371	830
Emissions from tanker	399	4.6	380	779
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,347**	**45.7**	**3,771**	**8,118**
2-stroke engine tankers powered by LNG				
Upstream & midstream emissions	723	32.7	2,698	3,421
Liquefaction	450	4.5	371	821
Emissions from tanker	329	4.7	388	717
Final transmission & distribution	---	3.2	264	264
Combustion by final consumer	2,750	---	---	2,750
Total	**4,252**	**45.1**	**3,721**	**7,973**



GWP$_{100}$ of 29.8
methane
CO_2 other than from final combustion
CO_2 from final combustion of LNG
g CO_2-equivalents/kg LNG
0
2
4
6
8
10
12
Steam powered by heavy fuel oil
Steam powered by LNG
4-stroke powered by LNG
2-stroke powered by LNG



GWP100 of 29.8
g CO2-equivalents/MJ
200
100
0
coal
Natural gas
LNG, short cruise powered by LNG
LNG, long cruise powered by LNG
LNG, short cruise, heavy fuel oil
LNG, long cruise, heavy fuel oil