MIT JOINT PROGRAM ON THE SCIENCE AND POLICY OF GLOBAL CHANGE

2023 GLOBAL CHANGE OUTLOOK

CHARTING THE EARTH'S FUTURE ENERGY, MANAGED RESOURCES, CLIMATE, AND POLICY PROSPECTS

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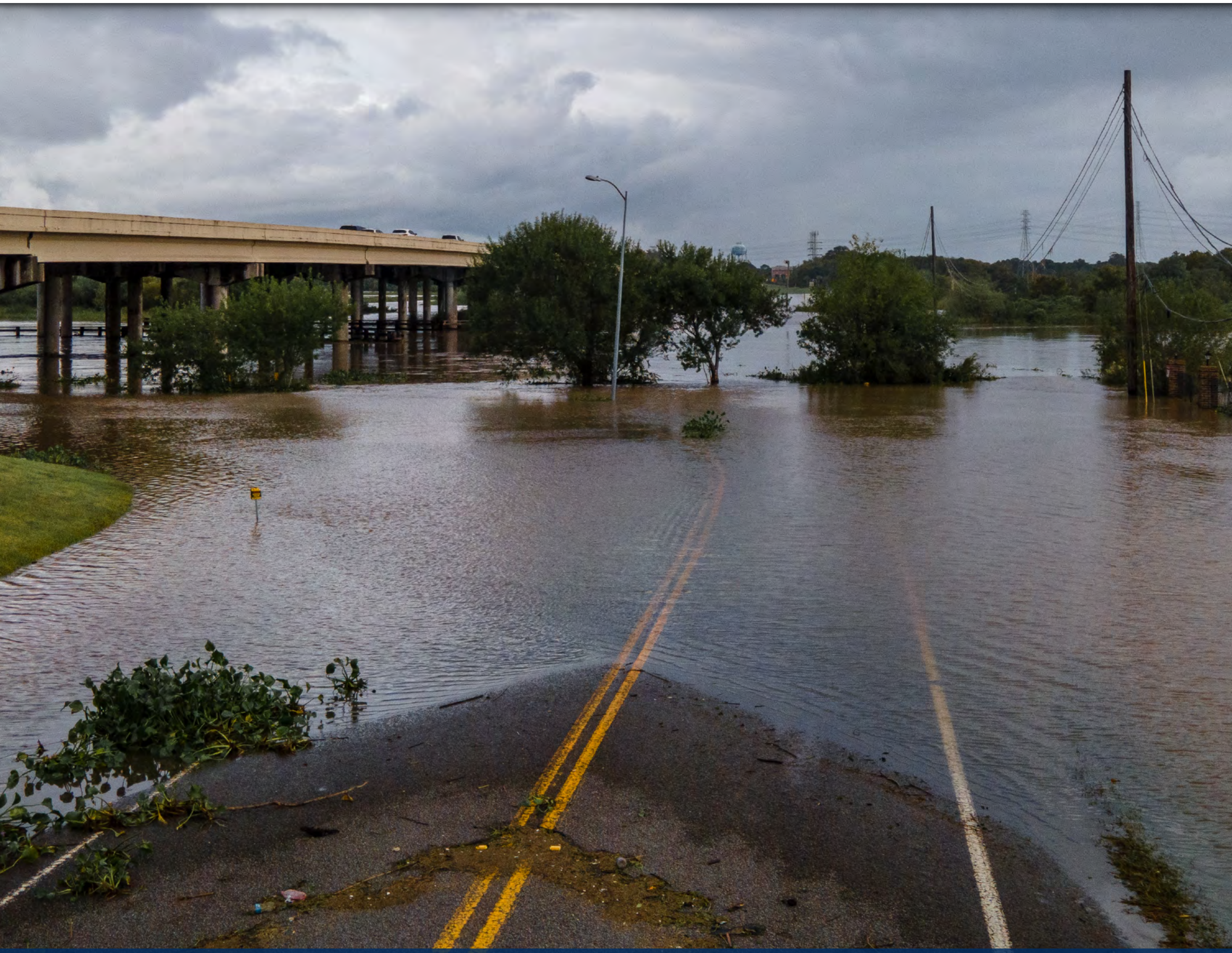

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

THE MIT JOINT PROGRAM ON THE SCIENCE & POLICY OF GLOBAL CHANGE

is working to advance a sustainable, prosperous world through scientific analysis of the complex interactions among co-evolving global systems.

MISSION

Advancing a sustainable, prosperous world through scientific analysis of the complex interactions among co-evolving global systems.

The pace and complexity of global environmental change is unprecedented. Nations, regions, cities and the public and private sectors are facing increasing pressures to confront critical challenges in future food, water, energy, climate and other areas. Our integrated team of natural and social scientists produces comprehensive global and regional change projections under different environmental, economic and policy scenarios. These projections enable decision-makers in the public and private sectors to better assess impacts, and the associated costs and benefits of potential courses of action.

VISION

We envision a world in which community, government and industry leaders have the insight they need to make environmentally and economically sound choices.

Toward that end, we provide a scientific foundation for strategic investment, policymaking and other decisions that advance sustainable development.

IMPACT

The MIT Joint Program:

- *Combines scientific research with risk and policy analyses to project the impacts of—and evaluate possible responses to—the many interwoven challenges of global socio-economic, technological and environmental change.*
- *Communicates research findings through our website, publications, workshops and presentations around the world, as well as frequent interactions with decision-makers, media outlets, government and nongovernmental organizations, schools and communities.*
- *Cultivates and educates the next generation of interdisciplinary researchers with the skills to tackle ongoing and emerging complex global challenges.*

2023 Outlook: Charting the Earth's Future

Energy • Managed Resources • Climate • Policy Prospects

The ***2023 Global Change Outlook*** continues a process, started in 2012 by the MIT Joint Program, of providing a periodic update on the direction the planet is heading in terms of economic growth and its implications for resource use and the environment. To obtain an integrated look at food, water, energy and climate, as well as the oceans, atmosphere and land that comprise the Earth system, we use the MIT Integrated Global System Modeling (IGSM) framework. Consisting primarily of the Economic Projection and Policy Analysis (EPPA) model and the MIT Earth System Model (MESM), the IGSM is a linked set of computer models developed by the MIT Joint Program to analyze interactions among human and Earth systems. As in our last (2021) edition, this year's Outlook reports on projected effects of population and economic growth, technology improvements, climate policy and other factors on energy and land use, emissions and climate, and water and agriculture. An important first step toward achieving stabilization of global average temperatures at reasonable cost is the Paris Agreement, in which nearly 200 countries committed to a wide range of initial climate actions aimed at achieving that goal. For this year's Outlook, we have invited guest contributors to offer perspectives on what's needed to accelerate innovation in climate mitigation and adaptation. Recognizing the inadequacy of the short-term commitments to keep global warming below the long-term targets of 2°C or even 1.5°C, we explore an emissions pathway consistent with the latter goal.

CONTENTS

About the 2023 Outlook

The 2023 Global Change Outlook presents the MIT Joint Program's latest projections for the future of the Earth's energy, managed resources (including water, agriculture and land), and climate, as well as prospects for achieving the Paris Agreement's short-term targets (as defined by Nationally Determined Contributions, or NDCs) and long-term goals of keeping average global temperatures below 2°C or even 1.5°C.

As with previous Outlooks, our intent is to represent as best we can the existing energy and environmental policies and commitments along with potential future pathways. This year's report is based on the latest version of our central economic model, the Economic Projection and Policy Analysis (EPPA) model, as well as revisions to our MIT Earth System Model (MESM). We use our Integrated Global System Modeling (IGSM) framework—which incorporates both models—to create large ensemble runs. This allows us to provide a full distribution of possible outcomes for a selected emissions scenario, given our uncertainty in climate response.

In the 2023 Outlook we focus on two scenarios. The first, which we call *Current Trends,* assumes that Paris Agreement NDCs are implemented through the year 2030. While our *Current Trends* scenario represents an unprecedented global commitment to limit greenhouse gas emissions, it fails to stabilize climate, allowing global average temperatures to continue to rise. We therefore consider an additional scenario that extends from the Paris Agreement's initial NDCs and aligns with its long-term goals. Referred to as *Accelerated Actions*, this scenario aims to limit and stabilize human-induced global climate warming to 1.5˚C by the end of this century with at least a 50% probability.

Online tables for 2020-2050 for these scenarios are available for each of the individual regions of our EPPA model (see **Box 1** for regional classification details for aggregate regions in this Outlook). Please note that units of measurement are based on the metric system, and all economic values are reported in 2021 US dollars. Our visualization tool explores these scenarios and expands climate outcomes to 2100.

The IGSM framework provides a unique capacity to project policy actions in tandem with the Earth system's response across its natural systems and managed resources. Additionally, complexities within both human/socio-economic systems and the Earth's response mechanisms lead to a variety of plausible futures under any proposed scenario. Through our IGSM ensemble-simulation approach, we can describe the range as well as the likelihoods of many plausible trajectories (see page 40).

While global-scale results provide important insights on the effectiveness of policy instruments (typically) driven by a global target, it is the more temporally and spatially granular aspects of these outcomes that directly associate with climate-related physical risks. To elicit that granularity, we have developed a "hybrid" downscaling method that incorporates the most recent climate-model information of emerging regional patterns of change that are associated with the human-forced global warming response. With these more spatially-detailed ensemble projections, we can provide more comprehensive synopses of climate-related physical risks. Together with transition risk assessments that can be done based on our scenarios, our tools offer a consistent framework for decision-making that incorporates physical and socio-economic components of climate risks.

Key Terms:

CCS	Carbon Capture and Storage
CO_2e	CO_2 equivalent
EPPA	MIT Economic Projection & Policy Analysis (model)
GHG	Greenhouse Gases
IGSM	Integrated Global System Modeling (framework)
IPCC	Intergovernmental Panel on Climate Change
MESM	MIT Earth System Model
NDC	Nationally Determined Contribution
UNFCCC	United Nations Framework Convention on Climate Change
WRS	Water Resource System (model)

Units of Measurement:

°C	Degrees Celsius	**TWh**	Terawatt hours
EJ	Exajoules	**ppm**	Parts per million
Gt	Gigatonnes		

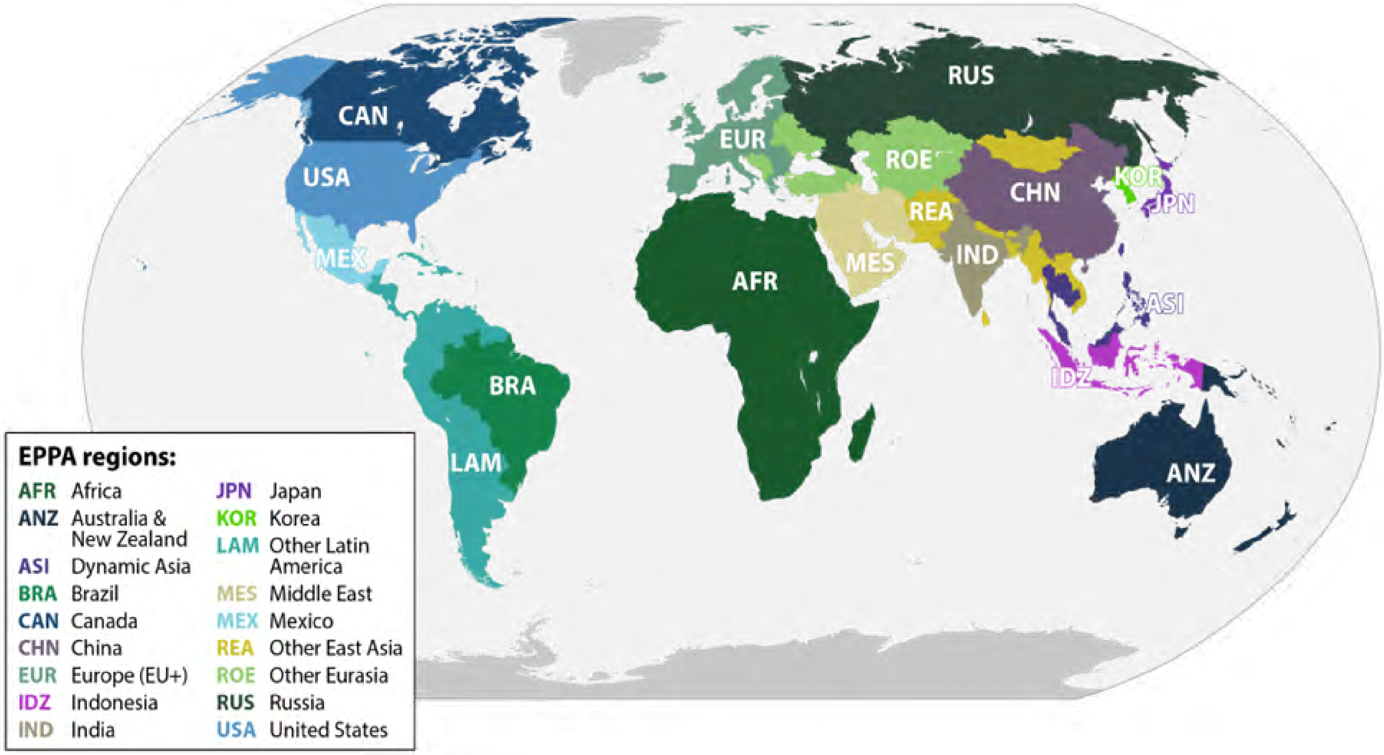

Figure 1. EPPA regions

Box 1.

Regional Classification Details

The Integrated Global System Modeling (IGSM) framework and its economic component, the MIT Economic Projection and Policy Analysis (EPPA) model, used to generate the projections in this Outlook, divide the global economy into 18 regions (see **Figure 1**). A full list of the countries included in each EPPA region is provided in the Outlook Appendix. Supplementary projection tables for 2020-2050 for all EPPA regions for the *Current Trends* and *Accelerated Actions* scenarios are available online at: http://globalchange.mit.edu/Outlook2023. For the reporting in this Outlook, the regions are further aggregated into three broad groups: *Developed*, *India & China* and *Rest of the World*. (see **Table 1**).

Table 1. Outlook regional classification

Regional Group	Region	Abbr.
Developed	United States	USA
	Canada	CAN
	Europe	EUR
	Japan	JPN
	Korea	KOR
	Australia, New Zealand and Oceania	ANZ
India & China	China	CHN
	India	IND
Rest of the World	Africa	AFR
	East Asia	ASI
	Indonesia	IDZ
	Other East Asia	REA
	Brazil	BRA
	Mexico	MEX
	Other Latin America	LAM
	Middle East	MES
	Russia	RUS
	Other Europe and Central Asia	ROE

Key Findings

Here we summarize the key findings of this report based on our modeled projections under two scenarios: *Current Trends* and *Accelerated Actions*. In broad terms, these scenarios correspond to either preserving existing climate policies or capping global warming at 1.5°C by 2100. More precise scenario definitions are presented in "Drivers of Global Change" on page 7. Most of our projections cover the 2020-2050 period, but some extend to 2100 and 2150. Finally, the findings shown below are largely at the global level; regional detail is provided in sections corresponding to each category and can be further explored through our Outlook online tables and visualization tool.

Energy

Population and economic growth are projected to lead to continued increases in energy needs and further electrification. Successful achievement of the Paris Agreement pledges will begin a shift away from fossil fuels, but additional actions are required to accelerate decarbonization.

Global Primary Energy

- Global primary energy use in the *Current Trends* scenario grows to about 650 exajoules (EJ) by 2050, up by 15% from about 560 EJ in 2020. The share of fossil fuels drops from the current 80% to 70% in 2050. Variable renewable energy (wind and solar) is the fastest growing energy source with more than an 8.6-fold increase in 30 years.
- In the *Accelerated Actions* scenario, global primary energy consumption declines after 2025 due to price- and policy-driven energy-efficiency measures, and reaches about 430 EJ in 2050. The share of low-carbon energy sources grows from 20% in 2020 to slightly more than 60% in 2050, a much faster growth rate than in the *Current Trends* scenario. Wind and solar energy in the *Accelerated Actions* scenario undergo more than a 13.3-fold increase.

Energy-Intensity Improvements

- Our projections show energy-intensity improvements from 2020 to 2050 in all economies. During this period, global energy intensity is projected to improve at an average annual rate of 2% in the *Current Trends* scenario, and 3.1% in the *Accelerated Actions* scenario.

Electricity Production

- In the *Current Trends* scenario, global electricity production (and use) grows by 73% from 2020 to 2050. In comparison to primary energy growth of 15% over the same period, electricity consumption grows much faster, resulting in a continuing electrification of the global economy. Generation from variable renewables exhibits the fastest growth (see Global Primary Energy, above).
- In the *Accelerated Actions* scenario, global electricity production grows even faster, rising by 87% between 2020 and 2050. More ambitious climate policies lead to a larger growth in variable renewables (See Global Primary Energy, above).
- Electricity generation from renewable sources becomes a dominant source of power by 2050 in both scenarios that we consider. To ensure a transition to low-carbon power generation in less economically developed regions, rich countries must provide sufficient technology transfer and financial support to incentivize further decarbonization.

Energy Prices

- In the *Current Trends* scenario, our modeling projects a rather stable crude oil price, with a five-year average of around $75/barrel. Global oil consumption also remains fairly stable. In the *Accelerated Actions* scenario, this trend is changed by a decrease in oil demand after 2030. The oil price declines from about $75/barrel by 2025 to $60/barrel in 2050, a 20% reduction. In this scenario, global oil consumption drops from about 190 EJ in 2025 to about 105 EJ in 2050.
- Natural gas prices vary by region—rising with increased demand for replacing coal-based power generation, falling when renewables expand significantly. Coal prices also vary by region: prices decline in most regions due to reductions in demand for coal.
- The average global electricity price increases from 2025 to 2050 by 10% in the *Current Trends* scenario and by 40% in the *Accelerated Actions* scenario. Price increases are mostly driven by policy requirements to include more low-carbon generation options.

Scaling Up Low-Carbon Solutions

- Due to a sizeable need for hydrocarbons in the form of liquid and gaseous fuels for sectors such as heavy-duty long-distance transport, high-temperature industrial heat, agriculture, and chemical production, hydrogen-based fuels and renewable natural gas remain attractive options, but the challenges related to their scaling opportunities and costs must be resolved.
- The scenarios considered in this Outlook may be affected by the pace of technological development in existing low-carbon technologies, such as wind and solar (and energy storage technologies to address their intermittency). To realize their potential, challenges related to permitting areas for generation and transmission lines, as well as materials and critical minerals availability, should be addressed. A more proactive consumer acceptance of low-carbon lifestyles may contribute to a move towards a circular economy. To reduce the need for materials, demand-side management needs to be accelerated.

Emissions and Climate

It is widely recognized that the near-term Paris pledges are inadequate by themselves to stabilize climate. On the assumption that Paris pledges are met and retained in the post-2030 period with further emissions reduction efforts, future emissions growth will likely come from developing countries, accelerating changes in global and regional temperatures.

Emissions

- Global GHG emissions in the *Current Trends* scenario stay relatively constant, initially increasing from about 47 gigatonnes of CO_2euivalent (Gt CO_2e) in 2020 to about 48 Gt CO_2e in 2030, and then gradually decreasing to about 45 Gt CO_2e in 2050 due to policies in countries with more stringent emissions targets. In the *Accelerated Actions* scenario, global GHG emissions follow the same path as in the *Current Trends* scenario until 2025, and then more aggressive policies reduce them to 18 Gt CO_2e by 2050, a 62% decrease relative to 2020.
- Extending our projections to 2150, global CO_2 emissions in the *Current Trends* scenario remain relatively flat at about 30 Gt CO_2e, reflecting mild policies on energy and industrial emissions. Moreover, our global GHG emissions projection shows a gradual increase in agriculture-related CH_4 and N_2O due to global population and GDP growth. In the *Accelerated Actions* scenario, global GHG emissions start to decrease after 2025. Global CO_2 emissions approach zero in the second half of

the century, but non-CO_2 GHGs such as CH_4 and N_2O are still not fully eliminated because of agriculture-related activities.

Climate

- Carbon dioxide (CO_2) concentrations in the *Current Trends* scenario continue to rise throughout (and after) the 21st century. By the beginning of the 2040s, the entirety of the Integrated Global System Modeling (IGSM) framework ensemble projection rises above 450 ppm of global CO_2 concentration. In addition, by mid-22nd century, more than half of the IGSM ensemble runs (i.e., at least 50% probability) show CO_2 concentrations at double their current level. Also by that time, we project with nearly 75% likelihood that CO_2e concentrations will rise to *at least* double the current level.
- In terms of radiative forcing of climate, our *Current Trends* scenario is most closely consistent with the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) 6.0 scenario, in that a radiative forcing of 6.0 W/m^2 is almost attained in 2100. However, the *Current Trends* scenario shows no indications of climate-forcing stabilization (as in the RCP6.0 scenario). However, we find no likelihood of exceeding a radiative forcing of greater than 8.5 W/m^2 (as in the IPCC RCP 8.5 scenario) by mid-22nd century.
- By 2060, more than half of the IGSM ensemble's *Current Trends* projections exceed 2˚C global climate warming, a figure that rises to more than 75% by 2070 and more than 95% by 2090. By 2100, 95% of the IGSM projections indicate a global climate warming of at least 2.2˚C, and the central tendency (i.e., median) of the projected warming is 2.8˚C. All of the ensemble's warming projections exceed 1.5˚C warming after 2050. By mid-22nd century, the *Current Trends* projections show that the world experiences at least a 2.9˚C warming (95% of the IGSM ensemble warmer) and most likely a warming of 3.8˚C (median result). The strongest global climate warming indicated by our projections (95th percentile) would be 4.6˚C.
- Our latest climate-model information indicates that maximum temperatures will likely outpace mean temperature trends over much of North and South America, Europe, northern and southeast Asia, and southern parts of Africa and Australasia. So as human-forced climate warming intensifies, these regions are expected to experience more pronounced record-breaking extreme heat events.
- The MIT Earth System Model (MESM's) global hydrologic sensitivity ranges from 1.7–3.3%/˚C. In the *Current Trends* ensemble, the MESM's projected increase in global precipitation between today and mid-century is most likely (i.e., median result) to be 0.04 mm/day, approximately an additional 7,400 km^3 (or nearly 2 quadrillion gallons) of water that will be delivered from the atmosphere each year, which exceeds the current estimate of global, annual human water consumption (4,600 km^3). By 2100, the total change in precipitation will most likely rise by 0.11 mm/day (or 21,200 km^3/yr)—nearly triple that of the mid-century change.
- In the *Accelerated Actions* scenario, global temperature will continue to rise through the next two decades. By mid-century, global temperature will stabilize, and then slightly decline through the latter half of the century. By the end of the century, the *Accelerated Actions* ensemble scenario indicates that the world can be virtually assured of remaining below 2˚C of global-averaged warming.
- The *Accelerated Actions* scenario not only stabilizes global precipitation increase (by 2060), but substantially reduces the magnitude and potential range of increases to almost a third of the *Current Trends* global precipitation changes. Further evidence indicates that the hydrologic sensitivity of heavy and extreme precipitation events can be up to 5-10 times that of global mean precipitation. Thus, any global increase in precipitation conveys amplified risk of flooding worldwide. Therefore, these aggressive mitigation scenarios convey considerable reductions in flood risk as well as uncertainty in the proportion (and cost) of adaptive actions that would otherwise be required.

Managed Resources

Water and agriculture are key sectors that will be shaped not only by increasing demands from population and economic growth but also by the changing global environment. Climate change is likely to add to water stress and reduce agricultural productivity, but adaptation and agricultural development offer opportunities to overcome these challenges.

Water

- Under the *Current Trends* scenario by mid-century, approximately 5.8 billion people worldwide will be exposed to shortfalls in water supply (societal stress) across the major river basins where they reside. In addition, 3.75 billion people will be living within basins exposed to environmental water stress, and 3.2 billion people will be exposed to both societal and environmental water-stressed conditions.
- With a global population projected to reach 9.7 billion by 2050, the *Current Trends* scenario indicates that more than half of the world's population will experience pressures to its water supply, and that 3 of every 10 people will live in water basins where the compounding societal and environmental pressures on water resources will be experienced.
- Population projections under combined water stress in all scenarios reveal that the *Accelerated Actions* scenario can reduce by approximately 40 million the additional 570 million people living in water-stressed basins at mid-century. More than half of the combined water-stress trend is the direct result of population increases across major river basins that are water-stressed under present-day climate conditions.
- While we find a modest "co-benefit" of climate action to reducing the global extent of water stress, our results highlight that the majority of the expected increases in population under heightened water stress by mid-century cannot be avoided or reduced by climate mitigation efforts alone.

Agriculture

- Under the *Current Trends* scenario, the value of the overall food production increases by 90% from 2020 to 2050, crop production by 70% and livestock production by 61%. Food production grows faster than livestock and crop production, and populations trends are a key driver.
- Under the *Current Trends* scenario, greater agricultural yields will prevent high increases in prices. By 2050 food prices are only 1% higher than in 2020. Crop prices grow a bit faster (10%), while livestock prices rise by 26%.
- Under the *Accelerated Actions* scenario, the value of crop output at mid-century is 5% lower than in the *Current Trends* scenario, while the value of livestock output reduces by 9% and food output by 5%. Changes in prices are also quite modest, but most salient in livestock. By mid-century, prices of livestock products are highly impacted under *Accelerated Actions*, increasing by 26% from *Current Trends*, while prices of food products and crop products increase by about 3% and 2% respectively.

Land-Use Change

- Global land-use projections from 2020 to 2050 are quite stable. Natural forest areas decrease by 1.4% and natural grasslands by 3%. These are converted mostly to cropland areas, which increase by 7.5%, while pasture lands increase by only 1.8%.
- In the *Current Trends* scenario, acreage dedicated to biomass for energy increases by up to 46% by mid-century, but as it occupies only 3% of the total cropland area in 2020, it remains relatively small in 2050 (4% of the total cropland area).
- Very different dynamics distinguish changes in agricultural land and natural areas around the world. The Rest of the World region faces larger land-use changes than other regions, due to stronger population and income growth. Cropland area increases by 14% by 2050. Pasture area decreases by 2.5% by 2050. On the other hand, cropland in India and China decreases by 1.7% in 2050, while land for bioenergy grows by 78%, covering 4.3% of the total cropland area.
- Land-use changes in the *Accelerated Actions* scenario are similar to those in the *Current Trends* scenario by 2050, except for land dedicated to bioenergy production. At the world level, the *Accelerated Actions* scenario requires cropland area to increase by 1% and pastureland to decrease by 4.2%, but land use for bioenergy must increase by 44%.

Meeting Short-Term Paris Commitments

Numerous countries and regions are progressing in fulfilling their Paris Agreement pledges. Many countries have declared more ambitious GHG emissions-mitigation goals, while financing to assist the least developed countries in sustainable development is not forthcoming at the levels needed. In the Global Stocktake Synthesis Report, the U.N. Framework Convention on Climate Change (UNFCCC) evaluated emissions reductions communicated by the parties of the Paris Agreement and concluded that global emissions are not on track to fulfill the most ambitious long-term global temperature goal of the Paris Agreement (to limit warming to 1.5 °C above pre-industrial levels), and there is a rapidly narrowing window to raise ambition and implement existing commitments in order to achieve that goal. Our *Current Trends* scenario arrives at the same conclusion.

Long-Term Climate Stabilization Goals

The Paris Agreement established more precise long-term temperature targets than previous climate pacts by specifying the need to keep "aggregate emissions pathways consistent with holding the increase in global average temperature well below 2°C above preindustrial levels" and further adding the goal of "pursuing efforts to limit the temperature increase to 1.5°C." We find that those targets remain achievable, but they require much deeper near-term reductions than those embodied in the NDCs agreed upon in Paris.

Box 2 summarizes the major updates and changes in the 2023 Outlook. The remaining report describes the details behind these broad conclusions.

Box 2.

New in the 2023 Outlook

Policy scenarios

We focus on two scenarios, *Current Trends*, which describes the implementation of the current world economic and policy trajectories, and *Accelerated Actions*, which explores the implications of increased mitigation ambition.

Regional Reporting

For both scenarios, we provide Excel files with main economic, energy, emissions and land-use results for all 18 regions of our Economic Projection and Policy Analysis (EPPA) model. For the reporting in this Outlook, the regions are further aggregated into three broad groups: *Developed*, *India & China*, and *Rest of the World*. A new focus on India and China allows us to illustrate the importance of actions from the world's two most populated countries.

Updated modeling framework

We use a recently updated version of our Integrated Global System Modeling (IGSM) framework, which includes a new version of the Economic Projection and Policy Analysis (EPPA) model and revisions to the MIT Earth System Model (MESM). Key model updates include new projections of gross domestic product (GDP) and population growth, updated technology costs, and Earth-system response to changing emissions and concentrations.

Geopolitics

Considering impacts of Russia's invasion of Ukraine, our current projections show slower long-term economic growth in Russia and a change in natural gas exports.

Climate Impacts on the Economy

Based on information from the Climate Impact Lab for ~24,000 administrative units (counties or their equivalent) across the globe, we evaluate climate impacts on labor and the resulting GDP changes.

Climate, Air Quality, and Health

Using our new Tool for Air Pollution Scenarios (TAPS), we evaluate emissions of important trace gases affecting air quality and subsequently human health.

Downscaling Climate Response

Based on the emerging-pattern responses that we extract from Earth-system models participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6), we have expanded our "hybrid" downscaling of the MESM outputs to provide the climate drivers for the labor-impact assessment. In addition, we have also developed a capability to indicate regions where maximum temperature trends are more likely to outpace the rate of mean warming. In doing so, we identify hotspots where "unprecedented" extreme temperature events are more likely to unfold as human-forced climate warming intensifies.

Drivers of Global Change

In this section we describe the major drivers of global change represented in our Integrated Global System Modeling (IGSM) framework. These include population and economic growth, and energy and land-use policy scenarios, all of which influence our projections of energy, managed resources and climate in the coming decades.

Population and Economic Growth

Two key drivers of global change are population and economic growth. We adopt a central estimate of population growth based on the latest projections from the United Nations Population Division. According to this estimate, the global population grows from 7.8 billion people in 2020 to 9.7 billion in 2050, and to 10.4 billion in 2100 (**Figure 2**).

Population dynamics differ by regional grouping. In the Developed region, population remains relatively stable at about 1.1 billion throughout the century. In the region that combines India and China, population grows from 2.8 billion in 2020 to 3 billion in 2050 and then declines to 2.3 billion by 2100. India experiences faster growth in 2020-2050 than China. While India's population is projected to increase from about 1.4 billion to 1.7 billion, China's population is expected to decline from about 1.4 billion in 2020 to 1.32 billion in 2050.

In contrast, population in the Rest of the World continues to increase from 3.9 billion in 2020 to 5.6 billion in 2050, and to 7 billion in 2100. Africa is the major contributor to this growth, with an especially high population increase between 2020 and 2050, from 1.3 billion to 2.5 billion, and a slower growth rate thereafter. The share of the Rest of the World region in global population rises from 49% in 2020 to 57% in 2050, and to 68% in 2100.

For our medium-term economic growth projections (up to 2050), we have revised economic growth in Russia downward (see **Box 3** on Energy Geopolitics) in comparison to our previous Outlook, while for other regions the rates are similar to our previous projections. For GDP growth rates after 2050, we assume constant productivity growth profiles based on the corresponding region-specific rates in mid-century. According to these projections, the average annual growth rate in world GDP is 2.5%

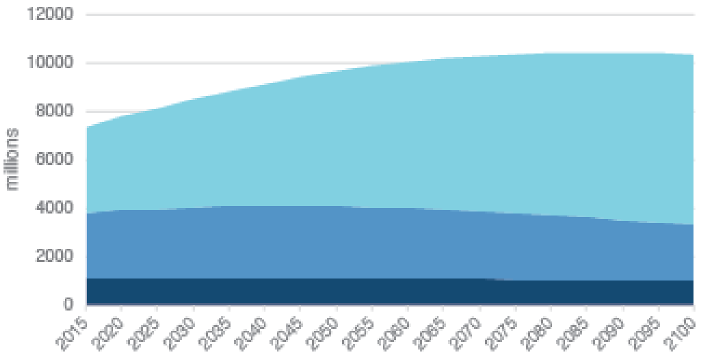

Figure 2. World population

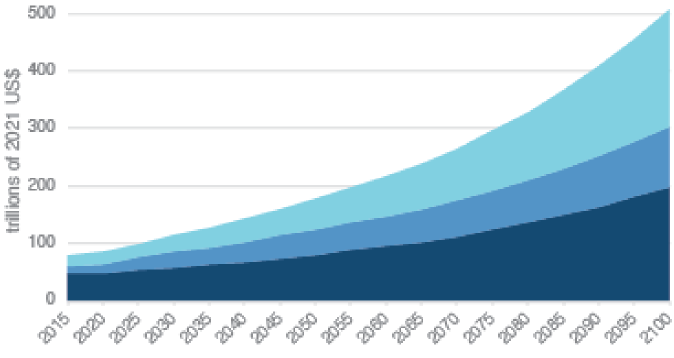

Figure 3. World GDP

Box 3.

Energy Geopolitics

Since the publication of our previous Outlook, geopolitical tensions have escalated on multiple fronts. First, Russia's invasion of Ukraine has created a global energy crisis, which has occasionally raised energy commodity prices up to ten times higher than historical levels. Second, U.S.-China relations, already soured by technology and trade conflicts, have grown even more tense over Taiwan, with visits of U.S. congressional delegations to the island nation inflaming those tensions. Meanwhile, concerns about energy security have become even more acute because of China's dominance in mining and processing of many critical minerals necessary for the clean energy transition. It is not surprising that the U.S. Inflation Reduction Act introduced domestic content provisions to "enhance national security," or that the European Union adopted a carbon border adjustment mechanism (CBAM) to "put a fair price" on goods from non-EU countries. Finally, an assault on Israel by Hamas has refueled fears of instability in the Middle East and its impacts on energy markets, especially on exports of oil and natural gas.

These and other geopolitical events have not only posed strategic challenges but also spurred increased investment in and deployment of clean energy as well as fossil-fuel-based energy technologies. They have also introduced more uncertainty in modeled projections of the world response to energy-transition and related policies. For example, our initial estimates of substantial impacts of the Western sanctions on Russia, including the oil embargo, have proven excessive. Countries like India and China, which refused to condemn or sanction Russia for its invasion of Ukraine, have helped Russia to fund its ongoing military activities. Measures implemented by Western countries have not been sufficiently stringent to prevent Russia from muting the effects of sanctions. As a result, while our current projections still show slower long-term economic growth in Russia and a reduction and reorientation of its natural gas exports, the impacts are more modest than in earlier projections.

One of the biggest geopolitical concerns in the energy sector is the growing need for scaling up the mining and processing of critical minerals needed for electric cars, wind turbines, solar panels and hydrogen production facilities. In addition to worries that supplies may increase too slowly to meet rising demand, the concentration of both mining and processing of critical minerals and clean energy technology manufacturing in a small number of countries creates energy security issues. As mentioned above, several countries have introduced measures to promote domestic production, but those measures may impose additional costs and inefficiencies on supply chains.

From international conflicts to the rise of renewable energy, energy geopolitics will likely influence the global balance of power for many years to come.

in 2020-2050, slowing to 2.1% per year for the period 2050-2100. Growth is slower in the Developed region, rising at 1.8% throughout the century. The India & China region grows at 3.1% per year in 2020-2050 and at 1.8% in 2050-2100. The Rest of the World grows at 3.3% in 2020-2050 and at 2.8% thereafter.

In contrast to population, most of the global economic value in 2020 was in the Developed region, which accounts for 56% of global GDP. Collectively, India and China, the two most populous countries in the world, constitute 36% of the global population but only 20% of the world economic value. The Rest of the World region has almost 50% of global population, but its economic wealth accounts only for 23% of global GDP. These trends persist throughout the century (**Figure 3**). Despite the higher economic growth in the Rest of the World region, its share of global GDP catches up with the Developed region only by the end of the century. The share of GDP of the Rest of the World region in global GDP slowly rises from 23% in 2020 to 30% in 2050, and to 40% in 2100. This result illustrates the remaining inequality among world regions in per capita income.

These trends in population and GDP increase pressure on natural resources, including energy, water and land. This pressure is offset in part by technological change that increases yields and reduces energy use per unit of production activity, and other broad-scale efficiency improvements.

Policy Scenarios

Also playing a key role in driving global change are climate policies (which include energy and land-use policies) that could significantly modify the effects of population and economic growth. We incorporate existing policies and measures in our projections, focusing on the emissions targets and policies identified in countries' Nationally Determined Contributions (NDCs) submitted under the Paris Agreement.

In this Outlook, we focus on the following scenarios:

- *Current Trends*, which assumes implementation of the current policy settings;
- *Accelerated Actions,* a 1.5°C stabilization pathway, in which countries impose more aggressive emissions targets that represent an illustrative pathway of increased mitigation.

Considerable interpretation is required to represent in our modeling system the approximate effects of policies and measures on emissions levels. In the *Current Trends* scenario, we include our assessment of commitments under the Paris Agreement for 2030. We rely on information from Climate Action Tracker and the UNFCCC Global Stocktake Synthesis Report to evaluate emissions reductions. We also include the emissions impacts of the Inflation Reduction Act in the USA. For methane reduction plans, we assess the Global Methane Pledge that aims to reduce global methane emissions by 30% from 2020 levels by 2030. We project that these policies will reduce emissions in the USA, Europe, the Middle East, Japan, and Brazil (see **Table 2**). While China and Russia are not participants of the Global Methane Pledge, we foresee sizeable reductions in those countries due to domestic actions (in China) and natural gas export declines (in Russia). We also include policies that aim to reduce deforestation as proposed at COP26. We project that these policies will be effective in reducing land-use emissions in many parts of the world, particularly in Africa, Brazil, Other Latin America and East Asia (see **Table 2**). Implementation of these policies leads to a reduction in global land use-related emissions by 47% in 2030 relative to 2020 levels.

Table 2. Change in methane and land-use CO_2 emissions in the *Current Trends* scenario

Outlook Regional Group	EPPA Region	Change in 2030 emissions relative to 2020 levels	
		Methane	Land-Use CO_2
Developed	USA	-28%	0%
	EUR	-23%	0%
	CAN	-7%	-9%
	JPN	-26%	0%
	KOR	-13%	-17%
	ANZ	0%	-30%
India & China	CHN	-17%	0%
	IND	24%	0%
Rest of the World	BRA	-27%	-85%
	IDZ	0%	-13%
	MEX	-7%	-21%
	RUS	-30%	-10%
	ASI	3%	-29%
	AFR	3%	-26%
	MES	-21%	0%
	LAM	-9%	-23%
	REA	11%	-30%
	ROE	-6%	0%

We also incorporate policies aimed at reducing reliance on Russian natural gas in Europe through energy savings, diversification of energy supply, and deployment of renewable energy as indicated in the REPowerEU plan.

While many countries are progressing in fulfilling their Paris pledges for 2030, even more aggressive global emissions reductions are needed for reaching the long-term goal of the Paris Agreement—"pursuing efforts to limit the temperature increase to 1.5°C". To evaluate the impacts of aligning emissions reductions with this goal, we explore the *Accelerated Actions* scenario in which countries impose much more aggressive emissions targets than those submitted in their NDCs.

In this scenario, we assume that advanced economies (USA, Europe, Canada, Japan, Korea, Australia and New Zealand) reduce their GHG emissions in 2050 by about 70-80% relative to 2015 levels. China reduces its emissions by about 70%. India reduces its CO_2 emissions by 50%, but because of growth in agriculture-related methane and nitrous oxide emissions, India's GHG emissions decline only by 13% in 2050 relative to 2015. Most other countries reduce their 2050 GHG emissions by 50-75% with respect to 2015 levels (except for Africa (45%) and Russia (85%)). These efforts by different countries result in global GHG and CO_2 emissions reductions in 2050 of about 65% and 75%, respectively, relative to their 2015 levels. While several countries have ambitious mid-century goals, many of the targets considered here do not represent actual policies in place or in planning. We explore them simply to illustrate the potential impacts of accelerated mitigation actions in alignment with capping global warming at 1.5°C.

Table 3. Emissions reductions in the *Current Trends* and *Accelerated Actions* scenarios

Outlook Regional Group	EPPA Region	Current Trends				Accelerated Actions			
		CO_2 emissions relative to 2015		GHG emissions relative to 2015		CO_2 emissions relative to 2015		GHG emissions relative to 2015	
		2030	2050	2030	2050	2030	2050	2030	2050
Developed	USA	-26%	-59%	-25%	-52%	-50%	-88%	-45%	-79%
	EUR	-23%	-44%	-27%	-46%	-45%	-73%	-45%	-71%
	CAN	-17%	50%	-17%	-49%	-35%	-82%	-34%	-80%
	JPN	-35%	-61%	-36%	-61%	-45%	-81%	-46%	-81%
	KOR	-17%	-51%	-18%	-50%	-25%	-67%	-26%	-66%
	ANZ	-8%	-39%	-17%	-40%	-22%	-78%	-30%	-72%
India & China	CHN	10%	-22%	10%	-20%	-25%	-75%	-22%	-67%
	IND	38%	47%	37%	59%	-2%	-50%	8%	-13%
Rest of the World	BRA	-45%	-44%	-36%	-35%	-48%	-85%	-41%	-76%
	IDZ	17%	0%	13%	6%	1%	-62%	-4%	-55%
	MEX	16%	26%	2%	12%	-23%	-71%	-30%	-68%
	RUS	1%	-5%	-7%	-15%	-23%	-91%	-26%	-85%
	ASI	15%	39%	11%	31%	-21%	-71%	-22%	-66%
	AFR	-7%	15%	-5%	19%	-10%	-59%	-10%	-45%
	MES	1%	41%	-5%	24%	-26%	-64%	-29%	-64%
	LAM	-7%	-5%	-10%	-10%	-24%	-65%	-25%	-60%
	REA	21%	59%	13%	43%	12%	-65%	4%	-50%
	ROE	25%	66%	13%	38%	-16%	-77%	-23%	-75%

The resulting emissions reductions by the EPPA model regions in the *Current Trends* and *Accelerated Actions* scenarios are provided in **Table 3**, expressed as percent reduction in CO_2 (including fossil, industrial and land-use emissions) and GHGs relative to 2015 levels.

Comparison to IPCC and IEA Scenarios

The Intergovernmental Panel on Climate Change (IPCC) in its latest assessment report (AR6) introduced two categories of 1.5°C-consistent scenarios, C1 and C2. Scenarios in the C1 category limit warming to 1.5°C (>50% probability) with no or limited overshoot, while the scenarios in the C2 category return warming to 1.5°C (>50%) after a high overshoot. High overshoot refers to temporarily exceeding 1.5°C global warming by 0.1-0.3°C for up to several decades. Our *Accelerated Actions* scenario fits well within the C2 range (see "Prospects for Meeting Long-Term Paris Goals" on page 43 for temperature results).

The International Energy Agency (IEA) has been a proponent of a scenario for reaching net-zero emissions in the global energy sector, the so called Net-Zero 2050 (NZE) scenario. In the original 2021 scenario and its recent 2023 update, total net energy sector CO_2 emissions reach zero by 2050. This scenario is consistent with the IPCC C1 category. The IEA reports that the global median temperature increase in this scenario is 1.4°C in 2100.

Our research shows that achieving global net-zero emissions by 2050 is not necessarily required in order to keep global warming at or below 1.5°C, and would add considerable policy costs, especially at mid-century (**Box 4** on Net-Zero Emissions by 2050, page 30). However, meeting the 2050 deadline would assure the achievement of the 1.5°C target.

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[PERSPECTIVE] Commercial fusion energy

A case study in advancing innovation for climate action

Anne White, School of Engineering Distinguished Professor of Engineering; Associate Provost and Associate Vice President for Research Administration; Co-Chair, MIT Climate Nucleus

MIT's climate action plan, titled "Fast Forward" because of the Institute's view that the world must dramatically accelerate the pace at which it responds to climate change, describes a need for action on two tracks at once.[1]

On track one, the plan argues, society must "go as far as we can, as fast as we can, with the tools and methods we have now." This means, among other things, driving adoption of commercially available clean energy technologies, including nuclear fission as well as wind, solar and energy-storage solutions; deploying more electric vehicles and heat pumps; building out reliable electrical infrastructure; and rapidly reducing methane emissions, especially from oil and gas operations.

On track two, we recognize that we don't yet have all the solutions: The world must develop, demonstrate, commercialize and scale up new technologies and strategies to reach net-zero emissions by mid-century. We'll need to reduce emissions from our hardest-to-decarbonize industries, develop cost-effective negative emissions technologies and find new ways to help communities prepare for and adapt to climate impacts. This will require both incremental advances — such as engineering cost reductions of emerging technologies — and dramatic breakthroughs built on decades of basic science.

To make rapid progress, universities around the world, including MIT, are ready to forge new, creative partnerships and consortia with industry and the public sector. The following example illustrates the value of sustained investment in innovation by government, academic and industrial stakeholders; in this case, it enabled a breakthrough in a potentially game-changing track-two technology: fusion energy.

Key innovation enables commercial development of new clean energy technology

In a fusion reaction, rather than splitting the atom, we combine nuclei to form heavier elements. Fusion reactions are four times more "energy-dense" than fission: you could power the city of Boston for a year using a volume of fuel that would fit in the bed of a pickup truck. Suitable fuel is abundant; one approach uses deuterium and tritium, sourced from water and rocks. Fusion produces no air pollution, greenhouse gas emissions or direct carbon emissions, and very little waste. In short, it generates ultra-clean energy, using the power of the stars here on Earth.

To achieve the fusion reaction, scientists heat a plasma to 150,000,000°C so that deuterium and tritium combine into helium atoms and free neutrons, releasing a colossal amount of energy. In a fully functioning power plant, the reaction should become efficiently self-heating and even regenerate some of its own fuel. The physics behind this, built on decades of basic science, is well-established. The engineering is now also at an inflection point.

To heat an untouchably hot plasma, we confine it using strong magnetic fields. One approach is to use low-temperature superconducting magnets in a tokamak the size of a playing field — but with high-temperature magnets, the tokamak can be significantly smaller. In an important breakthrough, researchers at MIT's Plasma Science and Fusion Center (PSFC), collaborating with startup Commonwealth Fusion Systems (CFS), demonstrated the world's strongest high-temperature superconducting magnet. Announced in September 2021, it achieved and sustained a 20-tesla magnetic field.[2] In effect, we now have the key technology needed to produce net energy from fusion in a tokamak reactor of a practical size.

The SPARC fusion reactor, the prototype now under construction at CFS' facility in Devens, Massachusetts, aims to achieve net energy generation from fusion by 2025, followed by construction of a pilot-scale power

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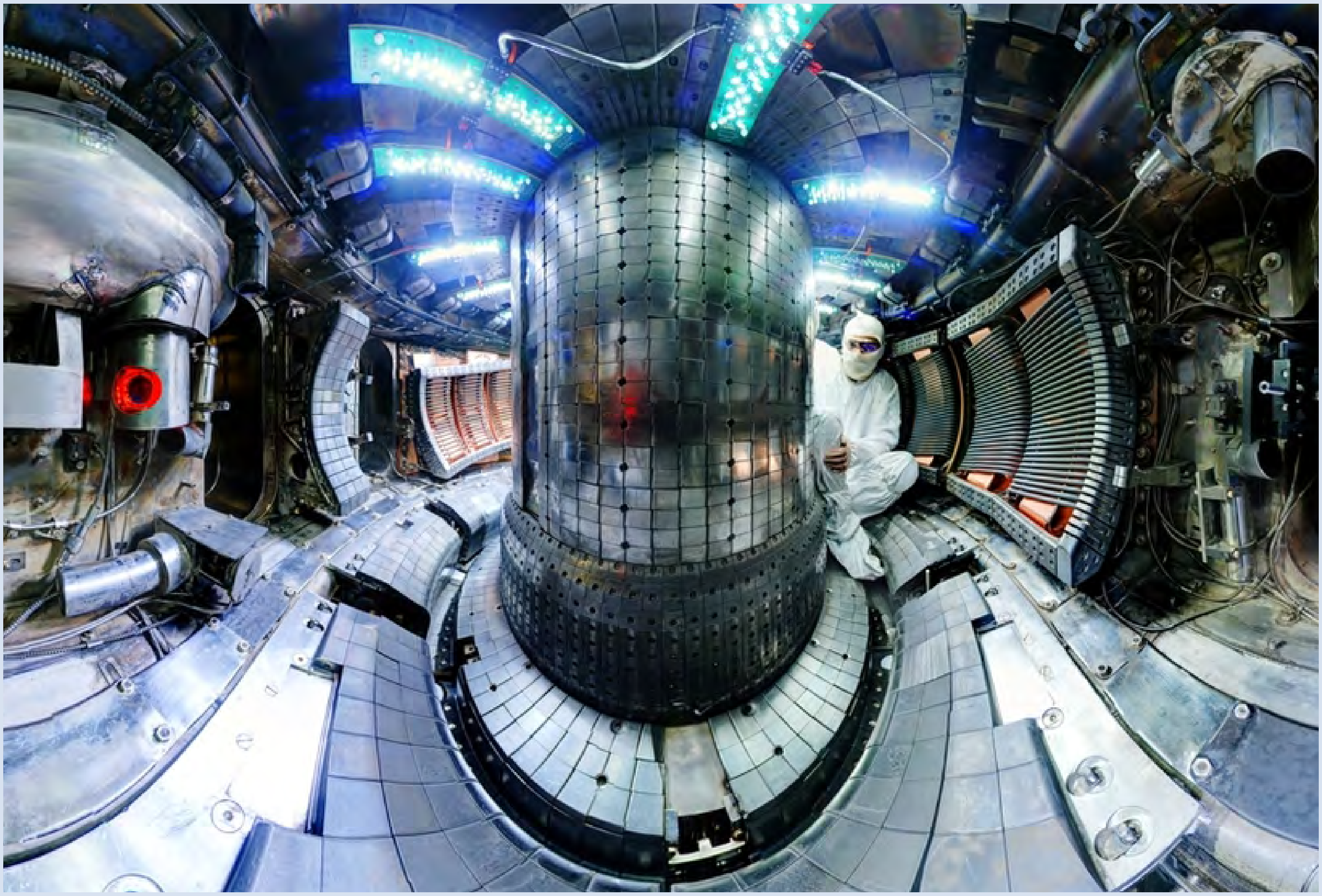
[1] "Fast Forward: MIT's Climate Action Plan for the Decade," https://climate.mit.edu/climateaction/fastforward.

[2] "MIT-designed project achieves major advance toward fusion energy," MIT News, Sept. 8, 2021: https://news.mit.edu/2021/MIT-CFS-major-advance-toward-fusion-energy-0908.



plant within 15 years. What's more, CFS is among at least 37 member companies of the Fusion Industry Association striving toward pilot-scale fusion power with a range of reactor designs and approaches.

Sustaining the innovation infrastructure for climate progress

What did it take to get to this point? To start: 65 years of sustained government investment in fusion research at universities, at the U.S. national labs and around the world. MIT established its first fusion energy program in 1958, opening a nuclear reactor on campus for research purposes. Subsequently, the PSFC, created in 1976, pursued the high-field path to fusion with a series of tokamaks from the 1970s up to 2016 that broke technical record after record.[3] Decades of fundamental advances were enabled by federal research funding and long-range vision.

The commercialization of very-early-stage technologies also requires scientists and engineers with an entrepreneurial mindset and leaders with strategic urgency. New models of funding and collaboration can attract early investment that enables a startup to begin commercial R&D while simultaneously supporting and accessing ongoing advancements in the science. In the case of CFS, an MIT spinout, engagement with Italian energy company Eni S.p.A. brought new sponsorship for fusion research on campus as well as significant investment in the startup.

The U.S. Department of Energy maintains its longstanding commitment to advancing fusion, recently awarding $46 million in new funding to help eight companies reach short-term technical milestones.[4] Meanwhile, federal policy is aligning to support regulated fusion power plants. And the private investment is clearly there: CFS raised $1.8 billion in Series-B financing.

This is what progress on track two requires: Strategic coordination across academia, government and industry; sustained commitment; parallel efforts; and innovative funding models to move everything faster, as time is of the essence.

Recent progress on fusion offers grounds for optimism, but it's critically important that it not provide an excuse for delaying progress on track one. In the near term, the most important thing we can do is dramatically accelerate the deployment of reliable, affordable, available tools, like wind and solar, as fast as possible.

Beyond making progress on tracks one and two, the Fast Forward plan highlights the importance of educating the next generation of leaders. Young people are inheriting a planet already changed irrevocably by older generations' actions with respect to greenhouse gas emissions. So with equal commitment, we must help our students thrive in the face of impacts they did not cause.

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[3] "New record for fusion," MIT News, October 14, 2016: https://news.mit.edu/2016/alcator-c-mod-tokamak-nuclear-fusion-world-record-1014.

[4] "DOE announces $46 million for commercial fusion energy development," May 31, 2023: https://www.energy.gov/articles/doe-announces-46-million-commercial-fusion-energy-development.

Energy

Primary Energy Consumption

Context

We depend on energy in our daily lives both directly, in activities such as food preparation, transportation and home heating, and indirectly, by using products manufactured with energy inputs. As a result, energy-related emissions are by far the largest contributor to human-caused GHGs in the Earth's atmosphere. Almost three-quarters of global GHGs come from energy consumption because the world still heavily relies on fossil fuels: in 2021, about 80% of global primary (i.e., pre-processed) energy consumption was based on coal, oil and natural gas. Reducing energy use through improvements in energy efficiency and transitioning from fossil fuels to lower-carbon energy sources (e.g., wind, solar, biomass, hydro and nuclear) is essential to decarbonizing economies, stabilizing the climate, and realizing a sustainable future.

Key Findings

We project that global primary energy use in the *Current Trends* scenario will grow from about 560 exajoules (EJ) in 2020 to about 650 EJ by 2050, a 15% increase in 30 years (**Figure 4**). In this estimate we include commercial fuels and traditional biomass use. The share of low-carbon energy sources grows from the current 20% to about 30% in 2050. Variable renewable energy (wind and solar) leads this growth with more than an 8.6-fold increase. Over the same period, nuclear power grows by 50% and hydropower grows by 48%. The use of modern biomass (e.g., commercial bioenergy used in transportation, industry and electricity) also increases, but because it is counterbalanced by a decrease in traditional biomass (e.g., collected wood for cooking and heating), total bioenergy grows by just 5% in this period. While these increases in low-carbon energy move the global energy system in the right direction, the speed of transition is not ambitious enough. Among fossil fuels, global natural gas consumption grows by about 20% between 2020 and 2050. Oil consumption (in our modeling, the liquids category consists mostly of oil, but also includes first-generation biofuels such as ethanol) grows by 7%, while coal consumption declines by 27%.

Our *Accelerated Actions* scenario shows a different trajectory over the same period. Global primary energy consumption declines after 2025 and reaches about 430 EJ in 2050. Price- and policy-driven energy-efficiency measures play a substantial role in reducing annual consumption. The share of low-carbon energy sources grows from 20% in 2020 to slightly more than 60% in 2050, a much faster growth rate than in the *Current Trends* scenario. Wind and solar energy in the *Accelerated Actions* scenario undergo more than a 13.3-fold increase. Nuclear power, hydropower and bioenergy grow by 160%, 65% and 20%, respectively. In contrast, consumption of all fossil fuels declines in this scenario: coal by 82%, natural gas by 73% and oil by 42%.

Primary energy consumption has different trajectories in the Developed, India & China, and Rest of the World regions. In the *Current Trends* scenario (**Figure 5**), energy consumption declines by 20% in the Developed region (driven by more aggressive emissions mitigation policies), while growth in energy use is 10% in the India & China region and 50% in the Rest of the World region. Different energy sources play different contributing roles in each region. While oil and gas still provide a large share of energy in the Developed region, the share of low-carbon sources grows from about 17% in 2020 to about 40% in 2050. At the same

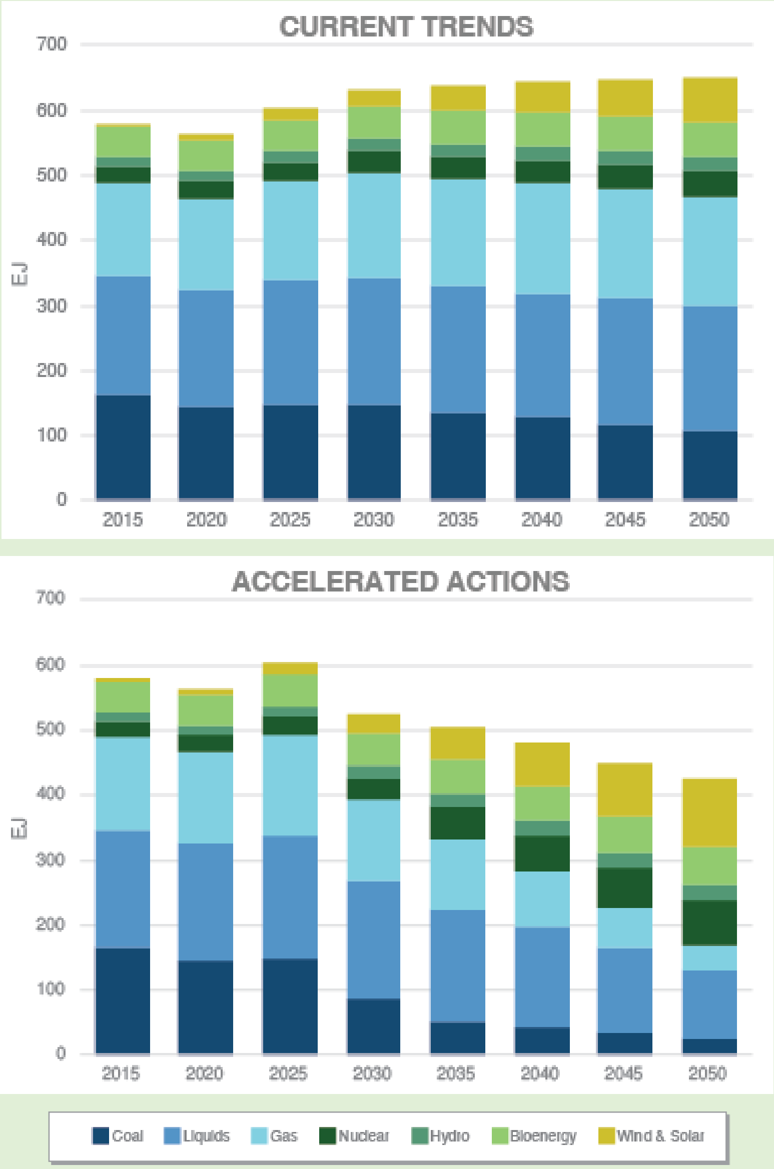

Figure 4. Global energy use (exajoules) in the *Current Trends* (top) and *Accelerated Actions* (bottom) scenarios

time, coal consumption declines substantially in the Developed region. However, in this scenario India & China continue to rely heavily on coal. Coal does not play a large role in the Rest of the World, but this region continues to consume large quantities of oil and natural gas.

In the *Accelerated Actions* scenario (**Figure 6**), total primary energy consumption declines from 2020 to 2050 in all three regions: in the Developed region by 36%, in India & China by 16%, and in the Rest of the World by 20%. In all three regions, we project a dramatic reduction in coal use, and substantial declines in natural gas and oil consumption. At the same time, wind and solar energy grow the fastest in all regions in this scenario: the increase is 9-fold in the Developed region, 10-fold in India & China and 45-fold in the Rest of the World.

Implications

The *Current Trends* in Paris Agreement pledges (made by countries for the year 2030) do not substantially decrease the share of fossil fuels in global primary energy consumption: from about 80% in 2021, it declines to about 70% in 2050. The required increase in ambition, represented by the *Accelerated Actions* scenario, moves the world away from fossil-fuel dependence much faster. Thus, additional policy actions are needed to speed up the energy transition towards low-carbon sources in all regions of the world.

More Information

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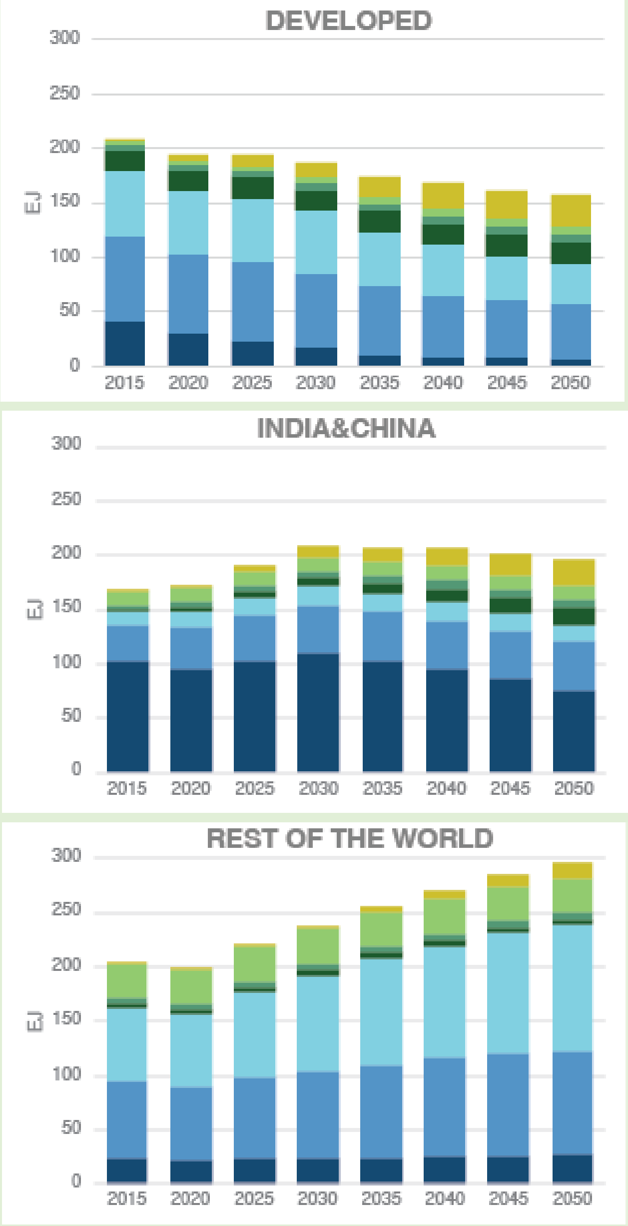
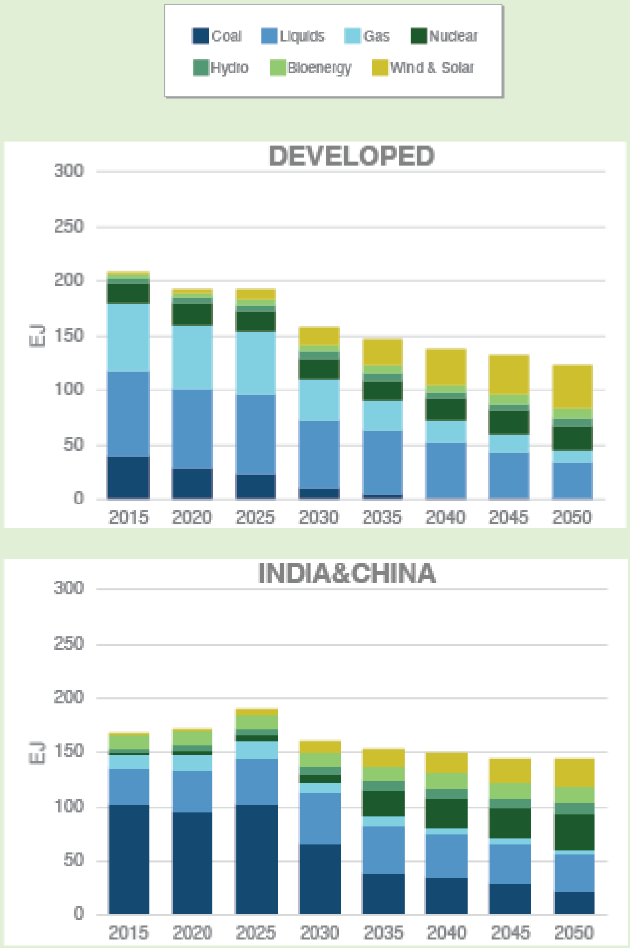


Figure 5. Energy Use (exajoules) in the *Current Trends* scenario by major group: Developed (top), India & China (middle), Rest of the World (bottom)



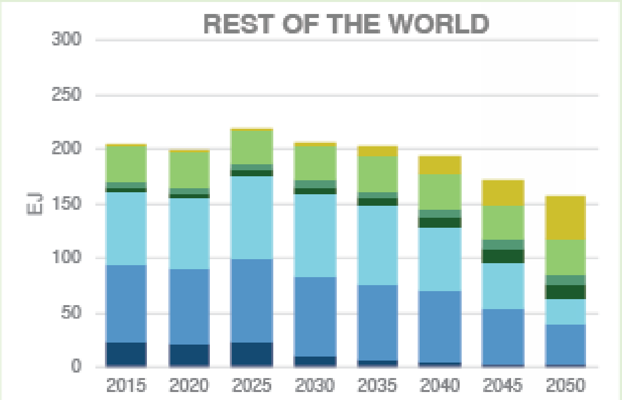


Figure 6. Energy Use (exajoules) in the *Accelerated Actions* scenario by major group: Developed (top left), India & China (left), Rest of the World (right)

Global and Regional Energy Intensity Improvements

Context

A measure of the energy inefficiency of an economy, energy intensity is defined as the number of units (e.g., exajoules) of energy per unit (e.g., US dollars) of gross domestic product (GDP). Through improvements in energy intensity, an economy can produce the same amount of economic output with less energy, thereby reducing its GHG emissions. Comparing absolute energy-intensity levels among countries is challenging due to varying climatic conditions, sectoral output compositions, and reliance on exports and imports. Moreover, GDP may be calculated using different methods such as at market exchange rates (as in this Outlook) or by purchasing-power parity. To adjust for the impacts of inflation, we use real GDP expressed in 2021 US dollars. Individual country intensities may also be affected by the balance between domestic production and import of energy-intensive goods. At the country or region level, the rate of energy-intensity improvement indicates technological progress, price-driven energy-efficiency improvements, shifts from energy-intensive industrial activities (e.g., to services), and other energy-related trends and policies.

Key Findings

In the *Current Trends* scenario, global energy intensity declines by 44% between 2020 and 2050; during that period, the world needs progressively less energy inputs to produce the same value of global goods and services. In 2020, global energy intensity was 6.6 EJ per trillion dollars. In 2050, it decreases to 3.7 EJ per trillion dollars. Converting to an annual average rate, global energy intensity improves at about 2% per year between 2020 and 2050 in this scenario.

Our projections show energy-intensity improvements from 2020 to 2050 in all economies (**Figure 7**). South Korea is the most rapidly improving county in the Developed regional grouping; its energy intensity improves at an annual average rate of 3.5% (which corresponds to a decreased energy intensity of GDP by 66% in the 30-year period). Annual average improvement rates for the USA, Canada and Australia/New Zealand (ANZ) are at 3%; Europe and Japan 2%; India 2.9%; and China 2.5%. For the Rest of the World, Africa improves faster than other regions, at 2.7%. Brazil, Mexico, Other Latin America, Indonesia, East Asia and Other East Asia improve at 2-2.2%. The Middle East and Russia are projected to have the slowest rates of improvement (1.5% and 1.1%, respectively) throughout the period, which reflects relatively lower fossil fuel prices and less aggressive energy and climate regulations in these regions.

In the *Accelerated Actions* scenario, the general tendencies are similar, but more aggressive climate policies lead to faster energy-intensity improvements. Globally, we project a reduction in energy intensity of GDP by 61% in the 2020-2050 period, which corresponds to a 3.1% per year improvement. Climate policies especially accelerate

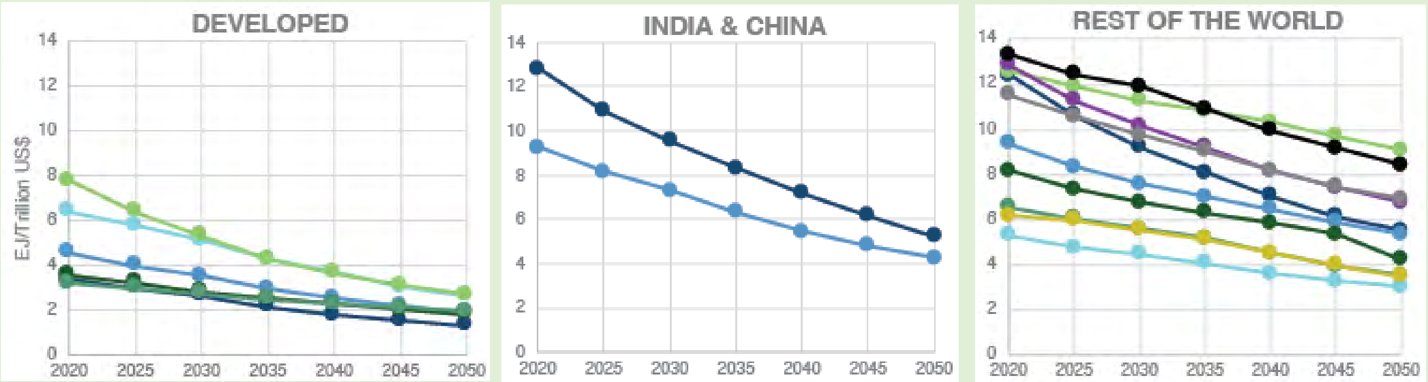


Figure 7. Energy Intensity (EJ/trillion US 2021$) in the *Current Trends* scenario by major group: Developed (left), India & China (middle), Rest of the World (right)

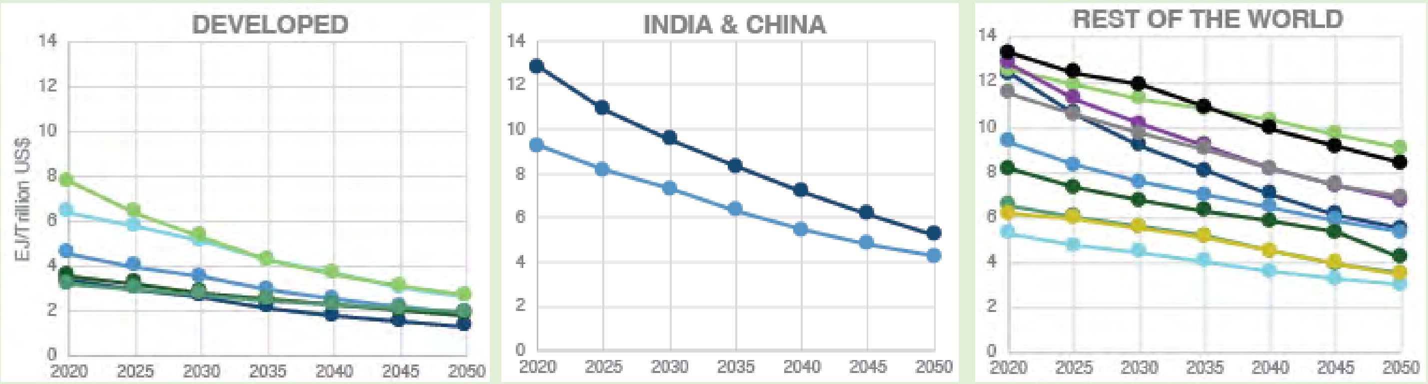


Figure 8. Energy Intensity (EJ/trillion US 2021$) in the *Accelerated Actions* scenario by major group: Developed (left), India & China (middle), Rest of the World (right)

improvements in East Asia, Africa, Rest of Europe, Australia/New Zealand (ANZ), USA and Korea (**Figure 8**), where the rates increase to 3.8-4.6%. The factors driving this acceleration include structural change, technological change, rising energy prices, and the rate of economic growth. Faster growth means higher investments; a greater portion of the capital stock incorporates newer, more energy-efficient technology. For Africa, the acceleration in energy-intensity improvement is also affected by forces related to the early stages of economic development.

Implications

Reducing energy intensity helps to provide the energy needs of a growing population seeking a higher quality of life. Achieving the same level of global economic output without energy-efficiency improvements would require more energy production. While global GDP is projected to double in 30 years, global energy consumption increases only by 15% in the *Current Trends* scenario and decreases by 25% in the *Accelerated Actions* scenario. With no efficiency gains, the world in 2050 would need to produce 80% more energy in the *Current Trends* scenario and 160% more energy in the *Accelerated Actions* scenario. Mobilizing investments in energy efficiency will be critical to avoid depletion of natural resources and transition to more sustainable and environmentally-friendly development.

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Electricity Production

Context

Electricity generation has several low-carbon options, such as wind, solar, hydro, nuclear, bioenergy, and the coupling of carbon capture with combustion of fossil fuels or biomass. With deployment of low-carbon electricity generation and accelerated electrification of transport, buildings and industry, substantial decarbonization of national economies can be achieved. To date, global growth in electricity demand has been addressed by installing both low-carbon and fossil sources. But in the coming decades, successful resolution of intermittency issues for variable renewables (wind and solar) will likely create a path for more rapid decarbonization not only in the Developed regions, but also in emerging economies. In addition, increased reliance on domestic wind and solar resources will lessen concerns about energy security by reducing or eliminating the need for importing fossil fuels.

Key Findings

In the *Current Trends* scenario (**Figure 9**), global electricity production (and consumption) grows by 73% from 2020 to 2050. Compared to primary energy growth of 15% over this period, electricity consumption grows much faster, resulting in a continuing electrification of the global economy. Generation from variable renewables grows the fastest, with an 8.6-fold increase. Biomass-based electricity production rises by about 90%, and nuclear and hydroelectricity by about 50%. The combined share of these low-carbon sources of electricity increases from about 38% in 2020 to about 68% in 2050. The contribution of fossil-based power generation decreases over time, both as a share of total generation and in absolute terms (in terawatt-hours, TWh). Petroleum-fired generation is small in 2020 and decreases further over time. Over the 30-year period, we project substantial switching from coal to natural gas generation, with coal decreasing by almost 50% and natural gas increasing by 50%.

In the *Accelerated Actions* scenario (**Figure 10**), global electricity production grows even faster, rising by 87% between 2020 and 2050. More ambitious climate policies lead to a larger growth in variable renewables, which increase 13.3 times. Bioenergy and hydro-based electricity grow by 188% and 65%, respectively. Nuclear generation also experiences a faster growth, rising 160% in this period. As a result, global power generation is largely decarbonized by mid-century, with low-carbon sources contributing more than 90% to total electricity production in 2050. While natural gas, coal and oil are still used, they all experience dramatic reductions, with coal decreasing by 85% and natural gas by almost 70% over the 30-year period.

Electricity production for major regional groupings in the *Current Trends* scenario is shown in **Figure 11**. In the Developed group over the 2020-2050 period, renewable (i.e., wind, solar, hydro, bio) generation grows, nuclear generation stays flat, natural gas-based generation is reduced by almost half, while coal generation quickly declines. In the India & China group, coal decline is smaller, while growth in renewables is more aggressive. Throughout the 30-year period, wind and solar generation grow twice as fast as in the Developed region. In the Rest of the World, renewables also grow, but natural gas is still the main option.

In the *Accelerated Actions* scenario (**Figure 12**), the general trends are similar, but with a faster growth in low-carbon options and decline in fossil-based options. Natural gas plays a much smaller role in Developed and India & China regions, and even in the Rest of the World we project a

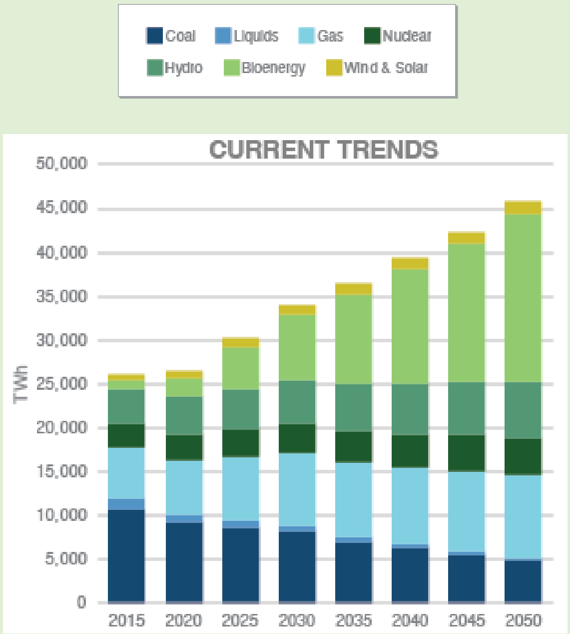

Figure 9. Global electricity production (terawatt-hour, TWh) in the *Current Trends* scenario

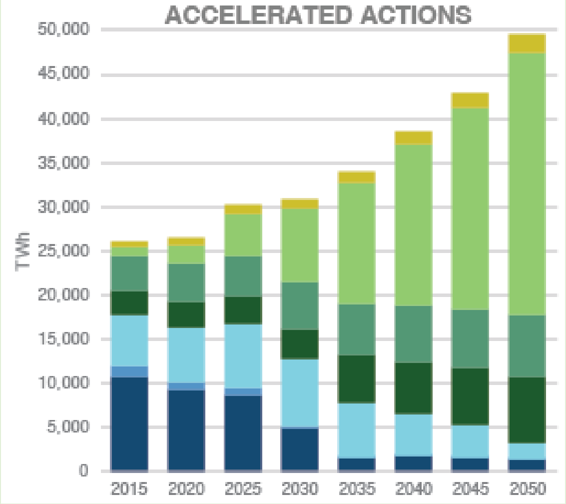

Figure 10. Global electricity production (terawatt-hour, TWh) in the *Accelerated Actions* scenario

substantial decline in natural gas-based generation by mid-century. All coal-based generation in this scenario is equipped with carbon capture and storage by 2050.

Implications

Electricity generation from low-carbon sources becomes a dominant source of power by 2050 in both scenarios that we consider. Most of the remaining coal generation is in India and China, where recently built coal plants are still operating in 2020-2050. But coal-based electricity declines even in those countries as renewables expand to fulfill the growing power-generation demand. In the *Current Trends* scenario, we project that natural gas expands in regions with less aggressive mitigation policies (such as Africa, the Middle East and Other East Asia). However, natural gas-based generation declines in these regions with more ambitious climate policies. To ensure a transition to low-carbon power generation in less economically developed regions, rich countries must provide sufficient technology transfer and financial support to incentivize further decarbonization.

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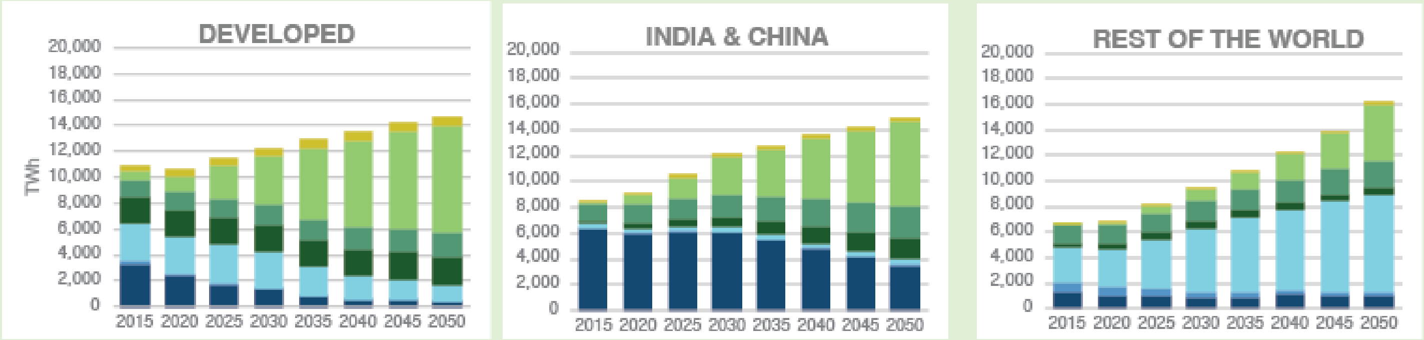

Figure 11. Electricity production (terawatt-hour, TWh) in the *Current Trends* scenario by major group: Developed (left), India & China (middle), Rest of the World (right)

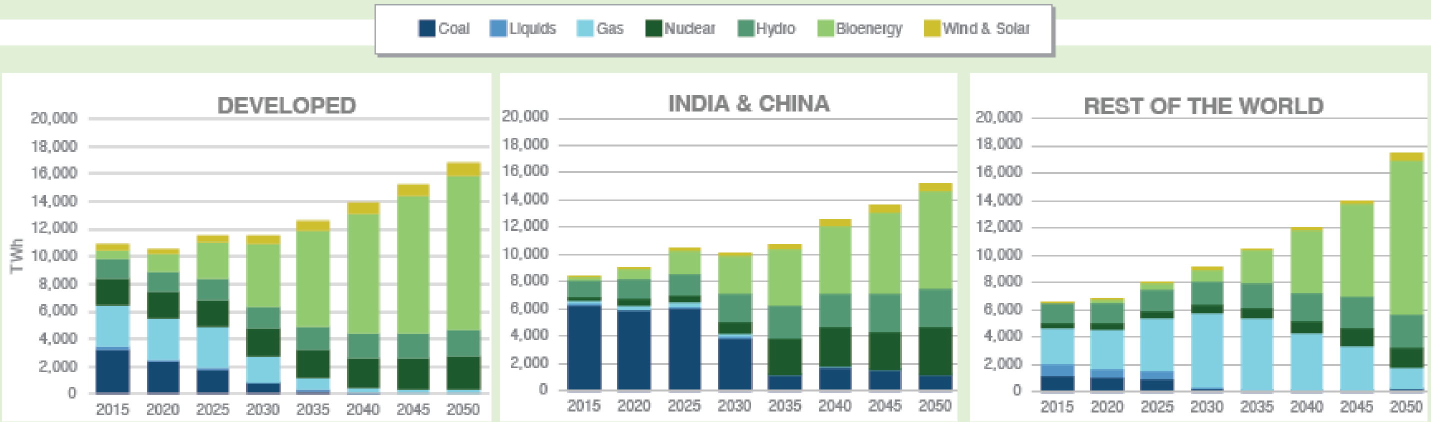

Figure 12. Electricity production (terawatt-hour, TWh) in the *Accelerated Actions* scenario by major group: Developed (left), India & China (middle), Rest of the World (right)

Energy Prices

Context

Energy prices are highly variable from year to year and subject to periodic large swings, sometimes dropping sharply within months and then reverting to earlier levels. The Covid-19 pandemic reduced demand for economic activities, resulting in a decrease in energy prices in 2020, but recovered energy consumption in 2021 and the Russian invasion of Ukraine in 2022 pushed prices up. As a result, while oil prices in 2020 were about $40/barrel, in 2022 average oil prices increased to about $100/barrel. A price rise for natural gas in Europe was even more pronounced, where the average annual price index in the Netherlands (TTF Index) grew from $3 per million British thermal units (Btu) in 2020 to more than $37/MBtu in 2022. While natural gas prices are lower in 2023 (about $15/MBtu in the Fall of 2023), oil prices remain high.

The EPPA model used for this Outlook focuses on long-term trends affected by underlying changes in supply and demand. We therefore project average prices for each five-year period between 2020 and 2050. We do not model processes that give rise to short-term commodity price dynamics, which include swings in expectations, depletion or accumulation of stocks, short-term disruptions to supply, and political factors. The model determines relative prices for all commodities explicitly represented. We then convert these price indices to price levels based on the corresponding historic prices in the base year.

Key Findings

Throughout the 2020-2050 reporting period, our modeling projects a rather stable crude oil price in the *Current Trends* scenario (**Table 4**) with a five-year average of around $75/barrel. Global oil consumption also remains fairly stable. In the *Accelerated Actions* scenario, this trend is changed by a decrease in oil demand after 2030. The oil price declines from about $75/barrel by 2025 to $60/barrel in 2050, a 20% reduction. In this scenario, global oil consumption drops from about 190 EJ in 2025 to about 105 EJ in 2050. While prices that oil producers receive for their products are decreasing, consumer prices are affected by taxes, standards and other policies.

Natural gas prices vary by region. In the USA we project a price of about $3-5.50/MBtu in both scenarios. In Europe natural gas prices stay at around $8/MBtu in the *Current Trends* scenario, but decrease to $6.59/MBtu in 2050 in the *Accelerated Actions* scenario due to substantial expansion of renewables and the virtual elimination of natural gas from power generation. China also expands renewables, but still relies on natural gas in industrial and residential sectors of its economy. Its natural gas prices stay at around $10/MBtu in the *Current Trends* scenario and increase to about $12/MBtu in the *Accelerated Actions* scenario.

Coal prices also vary by region, and we project stable or declining prices in most regions due to reductions in demand for coal. One of the few regions where coal prices are rising is Europe, where in the *Current Trends* scenario domestic coal production declines faster than the remaining (and decreasing) coal demand. In the *Accelerated Actions* scenario, coal in Europe is completely eliminated from the power generation sector by 2040, leading to a drop in prices. Because profit margins in coal production are low, prices do not decline dramatically, reflecting the cost of production for remaining volumes.

Electricity prices grow in both scenarios. While the changes differ by region, the average global electricity price increases from 2020 to 2050 by 20% in the *Current Trends* scenario and by 40% in the *Accelerated Actions* scenario. Price increases are mostly driven by policy requirements to include more low-carbon generation options. Variable renewables, such as wind and solar, are getting cheaper, but they make the electric grid more complicated, inducing integration costs. Also, in many developed countries, this requirement is coupled with overcapacity of old generation plants now producing at prices that are too low to recover the full cost of replacing these plants given current environmental policies. As long as this old capacity remains available, it can fill in for intermittent renewables. However, as it depreciates, higher prices are needed to encourage new capacity.

Table 4. Fossil fuel prices in different scenarios

Region	Scenario	2025	2030	2035	2040	2045	2050
				Crude oil ($/barrel)			
World	Current Trends	75	76	76	75	76	76
	Accelerated Actions	75	73	71	67	64	60
				Natural gas ($/MBtu)			
USA	Current Trends	3.92	3.43	3.18	4.09	5.00	4.95
	Accelerated Actions	3.92	5.21	5.16	5.27	5.40	5.30
Europe	Current Trends	8.24	8.24	8.15	8.25	8.40	8.37
	Accelerated Actions	8.24	7.94	7.71	7.34	6.98	6.59
China	Current Trends	10.34	10.23	10.19	10.20	10.36	10.36
	Accelerated Actions	10.34	12.26	12.22	12.14	12.64	12.79
				Coal ($/tonne)			
USA	Current Trends	39	36	33	32	32	32
	Accelerated Actions	39	31	30	31	33	33
Europe	Current Trends	52	80	108	133	127	111
	Accelerated Actions	52	46	41	39	40	43
China	Current Trends	87	77	79	66	65	63
	Accelerated Actions	87	59	53	54	55	55

Implications

Climate policies can be designed to reduce the appeal of fossil fuels. While natural gas may see some increases in demand (mostly in emerging markets) in the *Current Trends* scenario due to its lower carbon content relative to coal and oil, its use is projected to decrease under more aggressive emissions mitigation policies. In the *Current Trends* scenario, demand for fossil fuels remains substantial, and corresponding global energy prices remain rather stable. In the *Accelerated Actions* scenario, however, demand reductions more than offset cost increases due to resource depletion. As a result, both global coal and oil demand and prices are lower in 2050 in comparison to their levels in 2020, sending a notable signal to fossil-fuel developers about the risks of stranded assets and reduced or lost profits.

More Information

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Scaling Up Low-Carbon Solutions

Context

Rapid deployment of low-carbon solutions for energy, industry, agriculture and demand (i.e., those related to private and industrial consumption) sectors is key to a sustainable future. Scenarios, such as presented in this Outlook, are intended to show general pathways for achieving decarbonization of the economy, but do not capture many potential bottlenecks or unexpected technological advances. In addition to supply-side technologies, demand-side options that include new ways of providing services, reducing waste, recycling, improving energy efficiency, establishing adequate floor and office space, and extending product lifetimes are important to enhance. Climate mitigation also requires developing the necessary infrastructure to support advanced solutions, which, in turn, needs effective global cooperation to establish well-functioning markets. These challenges and opportunities may affect the pace of deployment for both the advanced technologies and demand-side options.

Key Findings

We project a substantial electrification of the economy and a large expansion of renewable sources for electricity production (see "Electricity Production" on page 15) over the next three decades. However, an "electrify everything and decarbonize electricity" strategy has its limits. While in the current Outlook, oil and natural gas consumption is projected to be lower than in the comparable scenarios of our previous Outlook (e.g., in 2050 in the *Accelerated Actions* scenario, the amount of oil and natural gas consumption are lower by 7% and 47%, respectively, relative to the corresponding 2050 values), we still project a sizeable need for hydrocarbons in the form of liquid and gaseous fuels for sectors such as heavy-duty long-distance transport, high-temperature industrial heat, agriculture, and chemical production.

Hydrogen-based fuels and renewable natural gas remain attractive options, but the challenges related to their scaling opportunities and costs must be resolved. Our studies on the use of hydrogen in steel-making, shipping and land transportation show that substantial government-supported R&D, infrastructure development and financial incentives will be needed to realize the potential of hydrogen-based solutions.

These findings are consistent with other projections. For example, while the International Energy Agency's latest Net-Zero Roadmap shows a reduced role for hydrogen-fueled trucks based on recent technology development trends, "green" hydrogen (based on water electrolysis powered by renewable energy) still plays a sizeable role by 2050 in the IEA's net-zero scenario.

To illustrate the scale of renewables needed for hydrogen production, the IEA's projected number of 39 EJ for global hydrogen production in 2050 can be used to calculate the amount of electricity generation required to produce this amount of hydrogen. Considering a typical electrolyzer's electricity consumption of 54 kWh/kg H_2, we estimate that 17,500 TWh of electricity would be needed if all produced hydrogen is green. The global electricity production in 2022 was about 29,000 TWh. This simplified calculation shows that the amount of wind and solar generation dedicated to hydrogen production in 2050 would be equal to 60% of the current total electricity generation from all sources and for all purposes. Developing and siting infrastructure for such a large expansion of wind and solar production would require substantial efforts, including advances in material efficiency and recycling.

The amount of solar and wind generation for the IEA-projected hydrogen production in 2050 is roughly consistent with the amount of solar and wind generation in our *Current Trends* scenario (**Table 5**). Based on National Renewable Laboratory estimates of land requirements for solar and wind, installing 1 Megawatt (MW) of solar power capacity requires 1 hectare (ha, 0.01 sq.km) and installing 1MW of wind requires 24.3 ha (0.243 sq.km). For wind, only 1-2% of that area is used directly by turbines and other supporting infrastructure, with the remaining area available for other purposes (e.g., farming). Applying these assumptions, we can estimate the land requirements for wind and solar in 2050 (**Table 5**). Some wind capacity (10% in 2050) is offshore and excluded for land estimates.

Our Outlook does not represent explicitly the economy-wide use of hydrogen, hence our projections for wind and solar generation might be underestimated. While our mitigation scenarios are less aggressive than the IEA's Net-Zero scenarios (and, as expected, our projections for wind and solar fall below the IEA numbers), we can compare the amount of wind and solar generation for similar IEA scenarios from their *World Energy Outlook*. In our *Current Trends* scenario, the global combined wind and solar generation in 2050 is about 19,400 TWh. In the *Accelerated Actions* scenario, it is about 29,100 TWh (**Table 5**). In the comparable IEA scenarios (Stated Policies and Announced Pledges), the corresponding values are 22,800 TWh and 36,200 TWh. Currently, global wind and solar generation is about 3,000 TWh. In all scenarios, wind and solar power sources grow rapidly by 2050.

Finally, we can estimate the amount of land required to scale up total wind and solar generation. In the *Current Trends* scenario, the land area required for global wind farms in 2050 is roughly equivalent to the area of a country similar to the size of Turkey. In the *Accelerated Actions* scenario, an area roughly that of Germany must be added to meet the total land requirement. Even with only 1–2% of windfarm area directly dedicated to wind turbines (and other space usable for farms, roads, etc.), the change in land use is quite substantial. The 2050 global area of land required for solar panels in the *Accelerated Actions* scenario is comparable to the area of Austria. While global wind farms and solar panels will be widely distributed around the world rather than concentrated in selected countries, this illustration provides a sense of the scale of land area required for global decarbonization efforts. Substantial technological improvements would be required to reduce land-use requirements, a particularly important consideration for countries with high population densities.

Scaling challenges and opportunities are also relevant for other key decarbonization activities, such as obtaining critical minerals for battery production. Demand-side mitigation and a shift to less energy-intensive practices, from telework to compact city planning, could make it easier to achieve energy transition goals.

Implications

The scenarios considered in this Outlook may be affected by the pace of technological development in existing low-carbon technologies, such as wind and solar (and energy storage technologies to address their intermittency). To realize their potential, challenges related to permitting areas for generation and transmission lines, as well as materials and critical minerals availability, should be addressed. Low-carbon pathways may also be impacted by numerous advances in different low-carbon solutions, such as hydrogen, direct air capture, advanced materials, biotechnologies, fusion and many others. A more proactive consumer acceptance of low-carbon lifestyles may contribute to a move towards a circular economy. To reduce the need for materials, demand-side management needs to be accelerated.

More Information

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Table 5. Global wind and solar generation and required land area in 2050 in different scenarios

	Current Trends	Accelerated Actions
Wind Generation (TWh)	11,171	15,872
Solar Generation (TWh)	8,212	13,227
Wind+Solar (TWh)	19,383	29,099
Land for onshore wind farms (sq.km)	803,377	1,141,456
Land for onshore wind turbines (sq.km)	16,068	22,829
Land for solar panels (sq.km)	48,433	78,011
Area of Turkey (sq.km)	780,000	
Area of Germany (sq.km)	360,000	
Area of Austria (sq.km)	84,000	

Climate

GHG Emissions by Gas/ Source and Region

Context

Anthropogenic greenhouse gas (GHG) emissions result from a wide range of industrial, agricultural and other activities involving the production or consumption of goods. Combustion of fossil fuels is by far the largest source of carbon dioxide (CO_2) emissions, and the largest source of anthropogenic GHG emissions. Methane (CH_4) is the second largest, but it has many sources, including those related to fossil energy production and distribution, agricultural activities and waste management. The largest anthropogenic sources of methane are livestock and rice production. Nitrous oxide (N_2O) arising from both fuel combustion and agricultural soils, but primarily nitrogen fertilizer, is the third largest source of anthropogenic GHG emissions. Industrial sources of CO_2, mainly from cement production, fluorocarbons (PFCs, HFCs, SF_6) and CO_2 related to land-use change, are smaller anthropogenic sources of GHG emissions. Anthropogenic emissions contribute indirectly to the formation of ozone and aerosols in the atmosphere, phenomena that we account for in our projections of future climate change.

Key Findings

We project that global GHG emissions in the *Current Trends* scenario will stay relatively constant, initially increasing from about 47 gigatonnes of CO_2equivalent (Gt CO_2e) in 2020 to about 48 Gt CO_2e in 2030, and then gradually decreasing to about 45 Gt CO_2e in 2050 (**Figure 13**) due to policies in countries with more stringent emissions targets. While GHG emissions in the Developed regional grouping decline by 43% in 2050 relative to 2020, and by 5% in the India & China region in the same period, this reduction is counterbalanced by an increase in GHG emissions in the Rest of the World, where emissions grow by 19% due to negligible mitigation policies.

In the *Accelerated Actions* scenario, global GHG emissions follow the same path as those projected by the *Current Trends* scenario until 2025, and then more aggressive policies reduce them to 18 Gt CO_2e by 2050, a 62% decrease relative to 2020 (**Figure 14**). In this scenario, emissions in all regions decline. In the Developed region they decrease by 72% from 2020 to 2050, with corresponding reductions in India & China and the Rest of the World of about 60%. Ambitious changes in current policy approaches will be needed to achieve emissions reductions of this magnitude.

We also extend our projections to 2150 (**Figure 15**) based on the scenario descriptions provided in "Drivers of Global Change" on page 7. While global CO_2 emissions in the *Current Trends* scenario remain relatively flat at about 30 Gt CO_2e reflecting mild policies on energy and industrial emissions, our global GHG emissions projection shows a gradual increase in agriculture-related CH_4 and N_2O due to global population and GDP growth. In the *Accelerated Actions* scenario, global GHG emissions start to decrease after 2025. Global CO_2 emissions approach zero in the second half of the century but non-CO_2 GHGs such as CH_4 and N_2O are still not fully eliminated due to agriculture-related activities. This scenario illustrates the required increases in global policy ambitions to meet the long-term goals of the Paris Agreement.

Implications

The Paris Agreement pledges made by countries for the year 2030 do not substantially decrease global GHG emissions, which start to grow again later in the century. Overall, emissions projections in our *Current Trends* scenario show trends similar to what we reported in our previous Outlooks, indicating insufficient action on GHG emissions mitigation, especially in emerging markets. While recent policies show some progress (in 2100, global emissions total 49 Gt CO_2e vs. 69 Gt CO_2e in the 2018 Outlook), the world is still not on track to achieve long-term climate stabilization. Ultimately, robust government policies will be needed for more aggressive GHG emissions mitigation.

More Information

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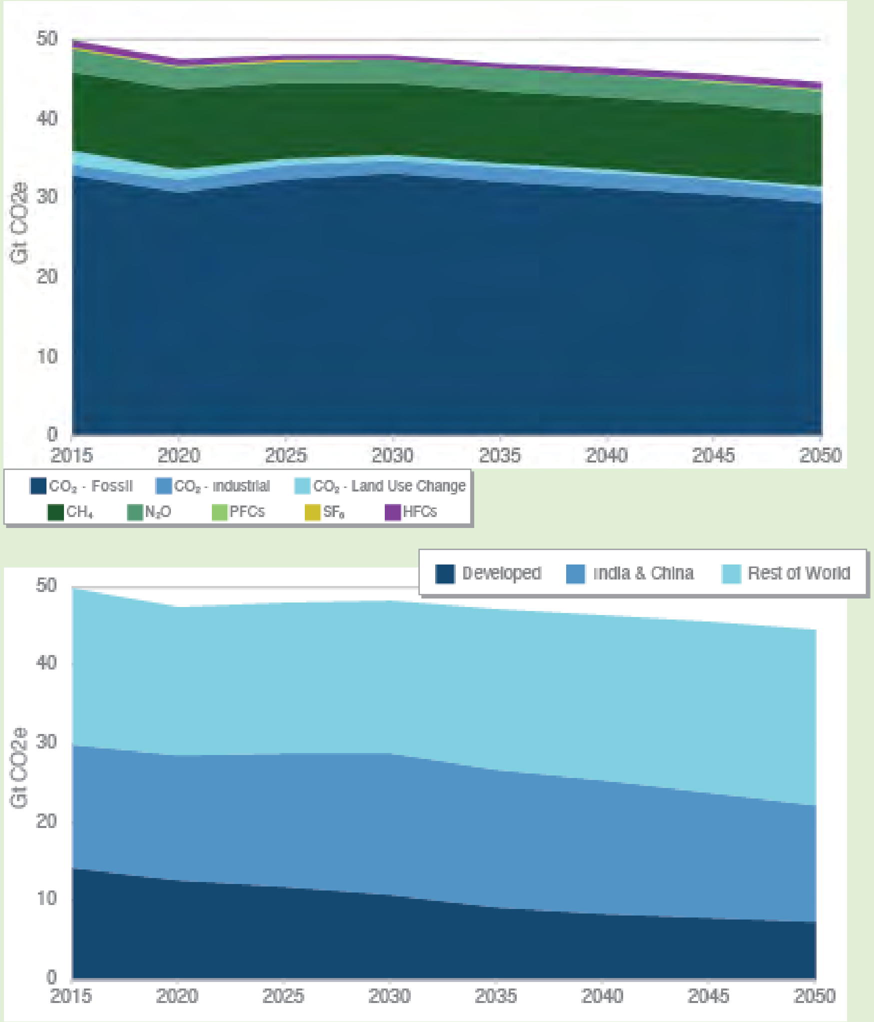

Figure 13. Global annual GHG emissions in the *Current Trends* scenario by gas (top) and regional group (bottom)

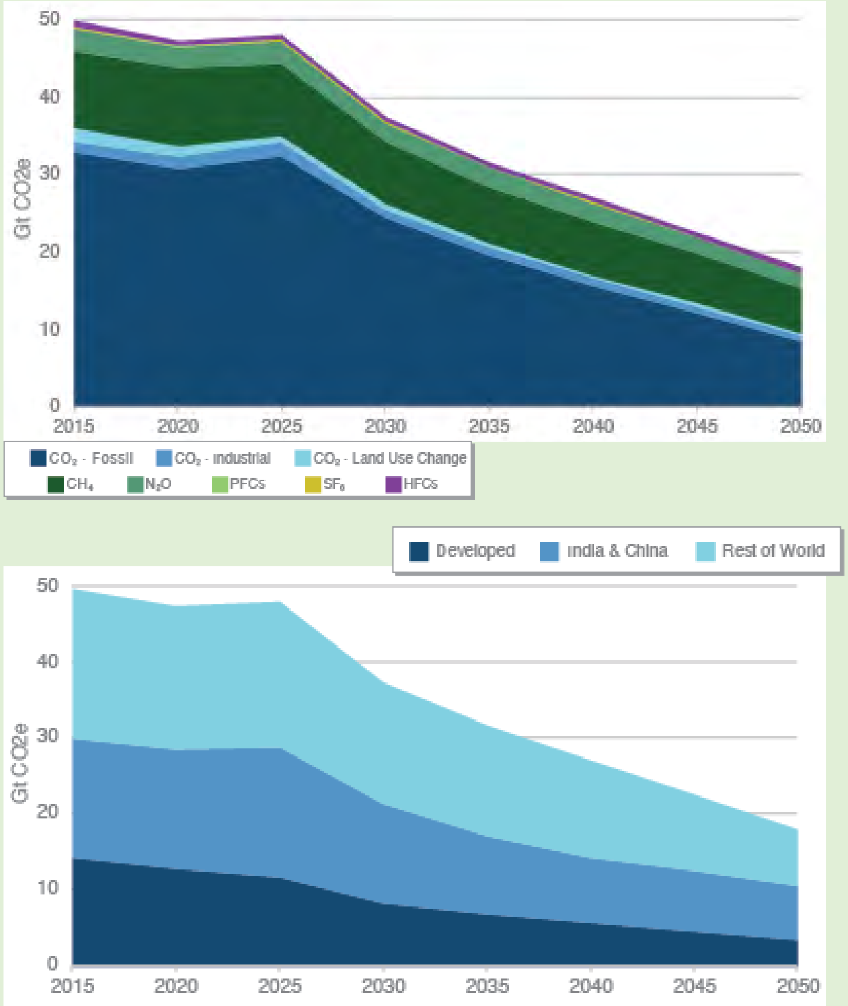

Figure 14. Global annual GHG emissions in the *Accelerated Actions* scenario by gas (top) and regional group (bottom)

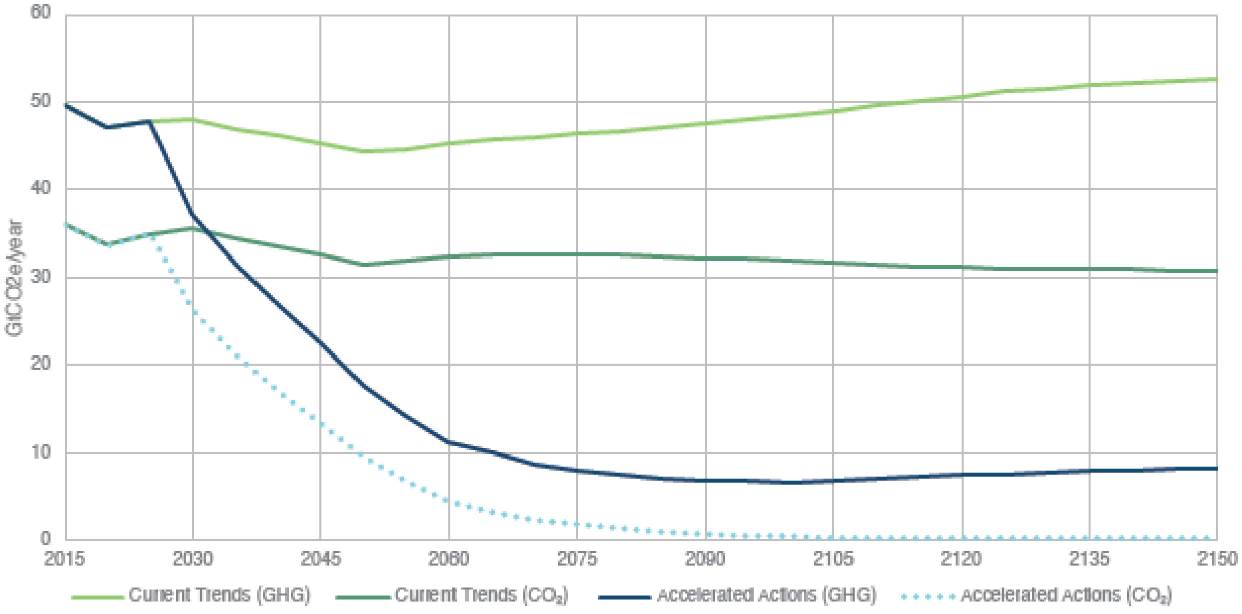

Figure 15. Global annual GHG emissions up to 2150

Global Climate Implications of the *Current Trends* Scenario Projections

Context

Anthropogenic emissions of greenhouse gases are the primary sources of interference in the Earth's (radiative) energy balance, which otherwise keeps the planet at a stable global temperature. By emitting and thereby increasing concentrations of radiatively-active trace gases, human activities promote additional global heating. The strength of this additional heating is defined as radiative forcing, or the net increase of energy (or heating) contained within the global climate system. In the previous section, we presented the Integrated Global System Modeling (IGSM) framework's projected trends in all relevant trace-gas emissions within the *Current Trends* scenario. To evaluate the potential effectiveness of these emissions-reduction commitments, we use the IGSM framework to model such actions and the Earth system's response in trace-gas concentrations, radiative forcing and global climate trends. However, complexities within both human/socio-economic systems and the Earth's geophysical, chemical and thermodynamical response mechanisms lead to multiple plausible futures under any proposed scenario. Through our IGSM ensemble-simulation approach, we can describe the range as well as the likelihoods of possible Earth-system responses, and in doing so, the effectiveness of a global policy and actions toward achieving a desired climate target.

Key Findings

We project that CO_2 concentrations in the *Current Trends* scenario will continue to rise at a steady pace through the rest of 21st century as well as through the middle of the 22nd century (**Figure 16**). When considering the emissions of all radiatively-active trace gases (including CO_2) and converting their concentrations into an equivalent CO_2 content (CO_2e), we project a slight acceleration in the rate of change of these concentrations at the onset of the 22nd century. This feature is aligned with a rise in the EPPA-predicted emissions of nitrous oxide, and to a lesser degree, methane.

In 2022, the global concentration of CO_2 (**Figure 17**) crossed an important echelon by surpassing 420 parts per million (ppm), and is now more than 50% higher than pre-industrial levels (estimated at 280 ppm). According to our *Current Trends* scenario projections, by the end of this century, there is a greater than 50% probability that the world will experience CO_2 concentrations exceeding 560 ppm, doubling pre-industrial levels. Moreover, by the middle of the next century, we project with nearly 100% likelihood that CO_2 concentrations will reach or surpass that mark. Finally, by 2150, we project a greater than 50% likelihood that CO_2e concentrations will rise to *at least* double the current levels.

The trends and likelihoods in radiative forcing of the global climate show similar steady rises. As a point of comparison, our *Current Trends* scenario is flanked by the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathways (RCPs) 4.5 and 6.0 scenarios. The RCP 4.5 and 6.0 scenarios achieve a radiative forcing of 4.5 W/m^2 and 6.0 W/m^2 at the end of the century, respectively. In the *Current Trends* scenario, we project with nearly 100% likelihood that the end-of-century radiative forcing will exceed 4.5 W/m^2 but not reach 6.0 W/m^2 (**Figure 18**). Yet unlike the RCP scenarios, radiative forcing in the *Current Trends* scenario continues to rise through the 22nd century and will surpass 6.0 W/m^2 with nearly 100% likelihood by 2150. However, we project no likelihood of reaching a radiative forcing greater than 8.5 W/m^2. Therefore, the IPCC's RCP8.5 scenario (8.5 W/m^2 radiative forcing),

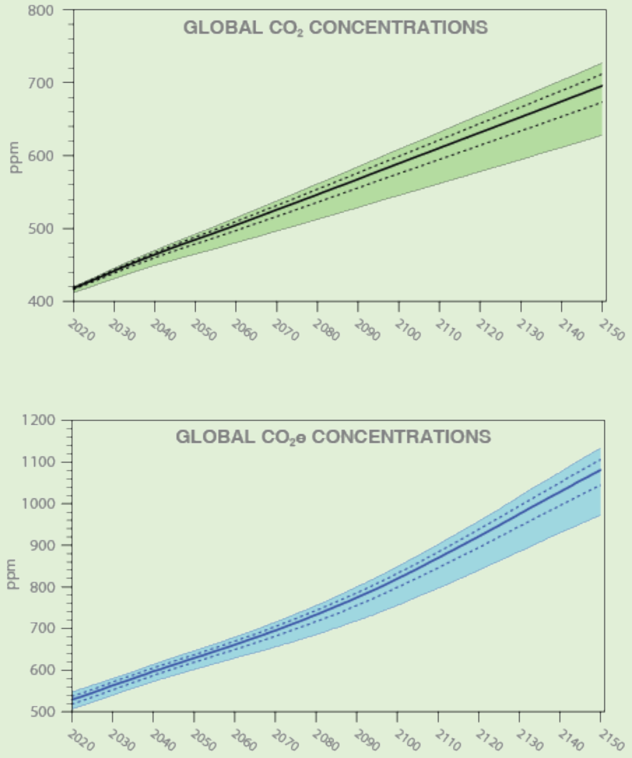

Figure 16. Global atmospheric concentration of carbon dioxide (top panel) and equivalent carbon dioxide (bottom panel), based on the *Current Trends* (CT) ensemble scenario. In each panel of results, the solid line represents the median result of the IGSM ensemble, the dashed lines denote the interquartile range, and the shaded region depicts the 5th to 95th percentile range of values. Units are in parts per million (ppm).

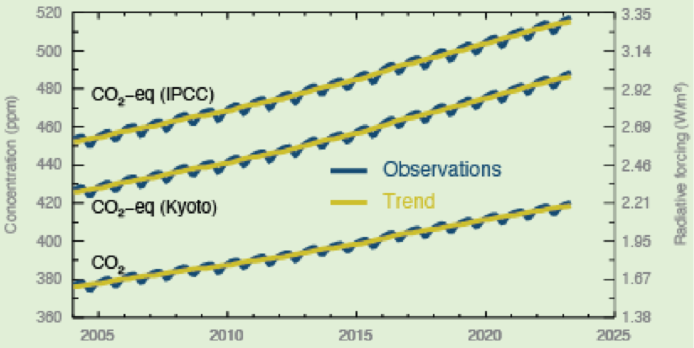

Figure 17. Concentrations (ppm) and corresponding radiative forcing (W/m^2) of CO_2 and equivalent CO_2 (CO_2e) following the approach described in Huang *et al.*, (2009). The non-CO_2 gas concentrations are measured by the AGAGE network (Prinn *et al.*, 2018) and the CO_2 concentrations are from the NOAA Monitoring Division (NOAA, 2018). The CO_2e concentrations are provided for both the IPCC and Kyoto catalogs of GHGs. For each of the observed timeseries (blue lines), the smoothed trend (red lines) is also provided.

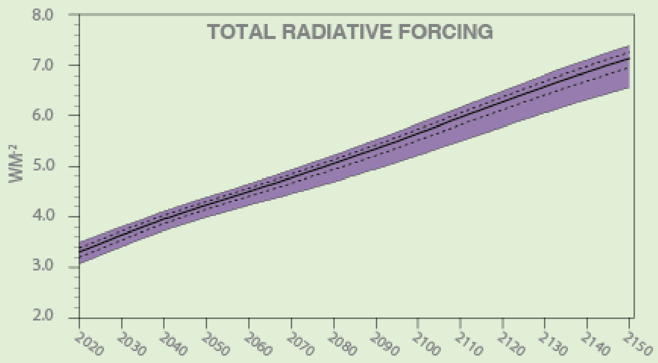

Figure 18. Total radiative forcing (units of W/m^2) that result from the EPPA emissions of radiatively-active gases, based on the *Current Trends* (CT) scenario. Values are calculated relative to 1861-1880. In each panel of results, the solid line represents the median result of the IGSM ensemble, the dashed lines denote the interquartile range, and the shaded regions depict the 5th to 95th percentile range of values.

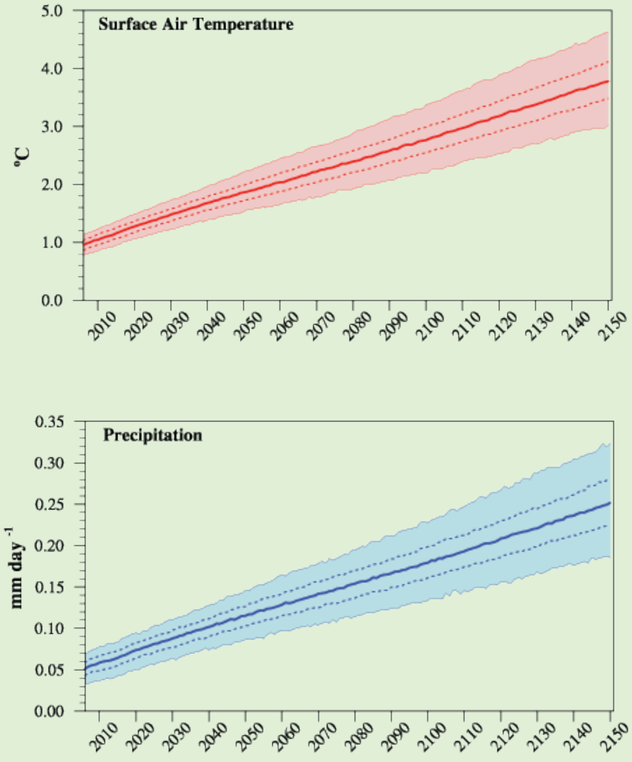

Figure 19. Annual changes in global mean surface-air temperature (top panel, in units of ˚C) and precipitation rate (bottom panel, in units of mm/day), based on the *Current Trends* ensemble scenario. Changes are calculated from the 1861-1880 mean. In each panel of results, the solid line represents the median result of the IGSM ensemble, the dashed lines denote the interquartile range, and the shaded region depicts the 5th to 95th percentile range of values.

used for numerous climate impact assessments and studies, must be viewed as extreme, if not highly improbable, under our *Current Trends* projections.

Nevertheless, the increases in human-caused radiative forcing under the *Current Trends* scenario cause important global climate responses (**Figure 19**); consequently, climate thresholds are crossed in the coming decades. One of the most recognized climate targets is to remain below a global climate warming of 2˚C (from pre-industrial levels). We find that by 2075, more than half of the IGSM ensemble's projections exceed 2˚C global climate warming, a figure that rises to more than 75% by 2085. By 2100, nearly 95% of the IGSM projections indicate a global climate warming of at least 2˚C, and the central tendency (i.e., median) of the projected warming is 2.5˚C. As for the Paris Agreement's most aggressive climate target of not exceeding 1.5˚C warming, the *Current Trends* ensemble scenario indicates no likelihood of fulfilling that objective—with the warming projections of all ensembles exceeding 1.5˚C warming after 2065. By mid-22nd century, the IGSM projections show that the world experiences at least a 3˚C warming (in nearly 95% of IGSM projections) and most likely a warming of 3.7˚C (median result).

A warmer climate will accelerate the global hydrologic cycle (i.e., increasing global evaporation and precipitation). The scientific community uses the term global "hydrologic sensitivity" to characterize the (relative) precipitation response to human-forced global warming. By this measure, the IGSM's global hydrologic sensitivity has been determined to range from 1.7 to 3.3 %/˚C. This range is slightly larger than the most recent estimates from the IPCC Coupled Model Intercomparison Project Phase 6 (CMIP6) climate models, found to be 2.1–3.3 %/˚C. Given this range in hydrologic sensitivity, we find that the most likely (median) increase in global precipitation between pre-industrial and present times is 0.05 mm/day. This amounts to approximately an additional 9,300 km^3 or 2.5 quadrillion gallons of water that will precipitate each year. In a recent assessment of the global "water footprint," it is estimated that the global impact of humans on water resources is 9,100 km^3 per year.

Under the *Current Trends* scenario, we project a continued steady rise in global precipitation consistent with the climate's "hydrologic sensitivity." This leads to an additional 0.05 mm/day rise in global precipitation by mid-century (with greater than 50% likelihood). By the end of the century, the total change in precipitation will most likely (greater than 75% likelihood) rise by 0.1 mm/day from current levels.

While these increases in precipitation may appear beneficial with respect to our water footprint, as we will discuss (in "Managed Resources" on page 36), this does not alleviate water stress and shortages faced by much of the world's population. These increases in precipitation do, however, indicate a rise in the risk of extreme precipitation events as well as the frequency and severity of flooding.

Implications

The projected global climate responses under the *Current Trends* scenario indicate that critical trace-gas concentrations will rise steadily and achieve important thresholds that are also aligned with potent global climate responses. While this scenario provides no mechanism to stabilize human-forced climate change through the mid-21st century, it represents a pathway to avoid the most extreme IPCC projection (RCP8.5) of human-forced climate change. Nevertheless, in order to stabilize and reverse human-forced climate warming, more action is needed. We highlight a more aggressive, accelerated climate-action scenario in sections that follow.

More Information

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[PERSPECTIVE]
Accelerating pro-poor investment and innovation in climate change adaptation

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Climate change affects everyone, but its damages will not be equally distributed. Low- and middle-income countries (LMICs) and communities, despite emitting the least, are projected to suffer the most, because they are more exposed to increasing extreme heat, floods and droughts, and have fewer resources to adapt.

Already the most severe health consequences, food insecurity and livelihood losses associated with climate change are concentrated in developing countries in Africa, South Asia, Latin America and Small Island Nations (IPCC, 2022b). Climate change may also push up to 130 million people into extreme poverty by 2030 (Jafino *et al.*, 2020).

This inequality also extends to climate finance: funding for adaptation is significantly less than what's allocated for mitigation. The UN Environment Program estimates the total funding that developing countries need is 5-10 times larger than total global investment in adaptation (United Nations Environment Programme, 2022), and as of 2021 only 7% of recorded global climate finance went to adaptation (Buchner*et al.*, 2021).

It's imperative that policymakers and funders increase their investments in adaptation, the same way they have risen to the challenge on mitigation, and prioritize viable solutions for those likely to be most adversely impacted by climate change: people experiencing poverty, people of color, indigenous peoples and other marginalized groups.

The global community can do three things to accelerate pro-poor climate change adaptation: (1) meet funding commitments to developing countries for adaptation and loss and damage, (2) use on-the-ground research to guide funding to the most impactful solutions, and (3) accelerate science on scaling effective and equitable adaptation solutions.

Increase adaptation finance, particularly for LMICs

To date, wealthy countries have not met the annual $100 billion commitment for climate finance for developing countries set at COP15 in 2009 (Abnett, 2022). This must be the year when we make good on this commitment by meeting or exceeding the target. That said, the COP27 commitment for a new loss-and-damage fund is an important achievement. COP28 is a crucial opportunity to establish a formal financing mechanism for this fund to ensure that pledges are met, whether through a small corporate or carbon tax in heavy-emitting industries and/or through a portion of foreign aid budgets, in addition to private and philanthropic commitments.

Once funding commitments are met, it is crucial to maximize their impact. First, reducing excessive review procedures of multilateral adaptation funds so that they can be disbursed within months, rather than years, is critical given the urgency of accelerating climate impacts (Beata and Mitchel, 2022).

Second, structuring a portion of adaptation finance to incentivize innovation, evaluation and scale can help accelerate the development of effective adaptation technologies and policies. This could take the form of open funding competitions that welcome civil society, governments, the private sector and universities to first propose innovative solutions, then test whether or not they benefit people in the real world, and finally scale those found to be effective in helping people adapt. This competitive staged funding model, pioneered by USAID's Development Innovation Ventures, has generated at least $17 in health and social benefits for people in LMICs per $1 spent (Michael *et al.*, 2021).

Use on-the-ground research to guide adaptation investments

The urgency of the climate crisis means we need to ensure that solutions achieve their intended goals. Climate risks also manifest differently in different places, so solutions must be tailored to local contexts.

Evaluating whether or not adaptation measures have tangible benefits for people in a particular place using rigorous evaluation methods such as randomized controlled trials provide a way to take action and learn whether the proposed solution works along the way. Since 2003, the J-PAL research network has conducted over 1,000 trials of real-world programs, including in climate change through the King Climate Action Initiative, which altogether have informed scale-ups of programs that have reached over 600 million people worldwide (Abdul Latif Jameel Poverty Action Lab (J-PAL), 2023.

Real-world trials can uncover important and surprising insights about how and why adaptation technologies succeed or fail. For example, recent trials by J-PAL-affiliated researchers and the International Rice Research Institute (IRRI) found that providing vulnerable farmers in India with flood-tolerant rice seeds increased their yields and revenue in both flood and non-flood years (Emerick *et al.*, 2016). Interestingly, 40% of these gains weren't due to the technology itself, but how farmers changed their behavior once they had access to it (Emerick *et al.*, 2016). Facing lower risk of crop loss, they invested more in their farms—cultivating more land and using more labor-intensive planting techniques (Emerick *et al.*, 2016).

This study suggests that improved seeds can work not only by protecting farmers from crop failure but also by inducing them to make higher-risk, higher-return investments. Researchers also found that the technology could benefit disadvantaged farmers the most because they are more likely to live on flood-prone land (Manzoor *et al.*, 2013). Following this study, IRRI distributed the stress-tolerant seeds to over 10 million farmers, and the Odisha State Seed Company increased production of the new seed variety.

Use science to accelerate technology diffusion and scale

Science also has an important role to play in identifying pathways for scaling up effective solutions. This includes testing incentives, information and marketing strategies, nudges[1] and policies to see what yields the biggest increases in adoption, and whether solutions maintain their effectiveness at scale.

Science can also be used to overcome barriers to scaling the many low-cost and effective adaptation technologies that already exist. A case in point: traditional rainwater harvesting techniques such as demi-lunes. These half-moon-shaped ditches, constructed by farmers on de-

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[1] A nudge is "any aspect of the choice architecture that alters people's behavior in a predictable way without forbidding any options or significantly changing their economic incentives," for example, by having the default option for a program be opt-out rather than opt-in (Thaler and Sunstein, 2008).

graded lands before the agricultural season begins, store rainwater underground and feed crops throughout the planting season. Researchers have long known that these techniques can help make arid lands arable again, particularly in Sahel countries such as Niger (Vohland and Boubacar, 2009). But despite its promise, adoption levels remain below 10% in Niger (Aker and Jack, 2023).

A recent trial by J-PAL-affiliated researchers in Niger found that training farmers to construct demi-lunes in a more accessible way—without needing to purchase our use new equipment, and building them on private land (where farmers get concrete benefits from them)—increased adoption of the technology by 90 percentage points. This, in turn, led to increased agricultural productivity and brought some previously infertile land back into production (Aker and Jack, 2023). The research team is now working with local partners to scale the training program up, while simultaneously testing ways to make the training cheaper and easier to implement with large numbers of people.

In sum, it's time for policymakers and researchers to prioritize investment and innovation in climate change adaptation, prioritizing communities and countries likely to be hurt most severely by climate change despite having done the least to cause it. In addition to increasing funding, investing in the global innovation and science ecosystem for adaptation can help accelerate the development of locally-relevant, effective and equitable adaptation solutions.

Climate Risk

Physical Risk

Regional consequences to global targets and prospects beyond 2100

Context

Physical risks across natural, managed and built environments will emerge, co-evolve and potentially compound as human-forced climate change progresses. While our global-scale results provide important insights on the effectiveness of policy instruments typically driven by a global target, it is the more temporally and spatially granular aspects of these outcomes that directly associate with climate-related physical risks. To elicit that granularity, the Integrated Global System Modeling (IGSM) framework's "hybrid" downscaling method combines the global-scale distribution of human-forced climate change with more spatially-resolved climate-response patterns to provide an objective sampling of the plausible outcomes that result from a global policy or environmental target.

Key Findings

To provide a broad assessment of emerging trends and their distributions across the world's major continental regions, we focus on changes in surface-air temperature and precipitation, which directly relate to the frequency and intensity of several high-impact climate- and weather-related events, including heat waves, floods and drought. One standout finding is that under our *Current Trends* and *Accelerated Actions* scenarios, all major continents will almost certainly pass 1.5˚C of warming by mid-century (**Table 6** and an example for North America shown in **Figure 20**). More precisely, in a *Current Trends* world, there is at least a 75% chance that across all continents, human-induced annually-averaged warming will exceed 1.5˚C by 2050—and by 2075 a nearly 95% chance that all continents but Oceania will experience annually-averaged warming greater than 2˚C. Our results also indicate strong seasonality in temperature trends, with continental regions experiencing stronger temperature increases during the cold seasons (see **Figure 20** and **Table 6**).

Recent "unprecedented" and record-breaking extreme temperature events worldwide have raised concerns as to whether these conditions can or will be increasingly expected to occur due to human-forced warming. Based on our latest climate-model information, we find that human-forced trends in maximum temperatures will likely outpace mean temperature trends over much of North and South America, Europe, northern and southeast Asia, and southern parts of Africa and Australasia (**Figure 21**). So as human-forced climate warming intensifies, these regions will likely experience more widespread and frequent record-breaking extreme heat events similar to those in recent years.

In view of all these temperature trends, the *Accelerated Actions* scenario indicates that many of the world's continents could warm above 2˚C by the end of the century. Specifically, North America and Asia have at least a 50% likelihood of annual-mean warming to at least 2˚C. On the other hand, Africa, Europe, Oceania and South America have at most a 25% likelihood of such warming.

Overall, human-induced climate warming drives a global precipitation response; a warmer climate acts to "accelerate" the hydrologic cycle leading to higher precipitation rates. This underscores an underlying threat of more flood-prone conditions. However, there are exceptionally important regional and seasonal departures. In particular, under the *Current Trends* scenario, we find that Europe will most likely experience widespread drier summer conditions (**Figure 22**) through the latter half of the century; North America (as well as the contiguous United States) shows a similar but less pronounced conditions. With less precipitation and warmer temperatures, this represents widespread, compounding risks of enhanced heat-stress and drought-prone conditions. For Europe, the central tendency of our projections aligns with this, yet the probability does not exceed 75% (see **Table 7**). Under the *Accelerated Actions* scenario, however, the prevailing risk of these summertime conditions is eliminated. However, an elevated risk of increased wintertime precipitation remains.

Implications

Our results underscore that elevated climate-related physical risks—including more pronounced extreme-temperature events (**Figure 21**)—will continue through mid-century and are largely unaffected by climate-policy actions. The salient benefits of climate actions are realized through the latter half of the century. This is a critically important aspect in the strategic planning and preparation to secure and sustain resource systems (land, water, energy), socio-economic sectors, equitable human health, and biodiversity. The "multi-sector" analyses that our researchers pursue takes all these factors into consideration, and brings the full spectrum of physical risks to bear toward a more holistic vision of sustainable development.

More Information

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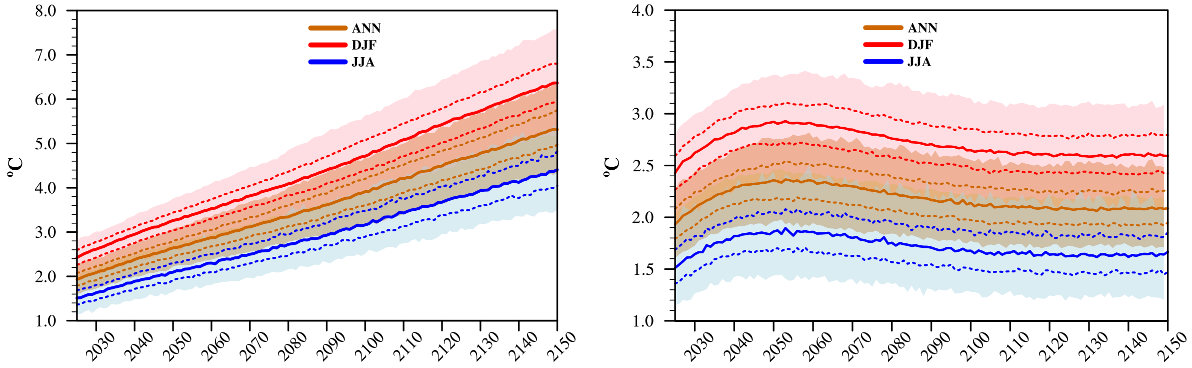

Figure 20. Projections for *Current Trends* (left) and *Accelerated Actions* (right) showing the range of outcomes in surface-air temperature change (˚C relative to pre-industrial average, 1860-1881) averaged over North America.

Note: Solid lines represent the median results. Dashed lines indicate the 5th and 95th percentile. Thin (colored) bars provide the interquartile range (25th and 75th percentile) about the median result. Results are shown for the annual (ANN) mean (brown lines), December-February (DJF) average (red lines) and June-August (JJA) average (blue lines). Created by combining IGSM global projections with spatial response patterns of climate change from the latest IPCC climate model simulations. This also applies to Figure 22 below.

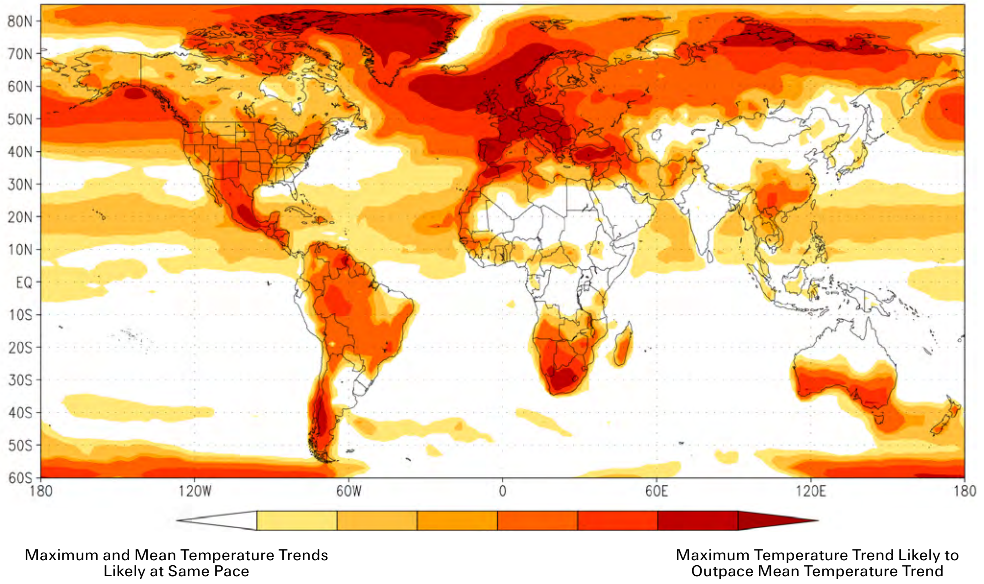

Figure 21. Map of an "Extreme Temperature Trend" index indicating the (unitless) relative degree and consensus to which daily maximum temperature trends outpace mean temperature change in response to human-forced climate warming. Consensus determined by the number of model responses that agree in the sign of temperature changes. IGSM "hybrid" downscaling based on aggregate climate-model response from the Coupled Model Intercomparison Project Phase 6 (CMIP6). Darker shades indicate greater likelihood of maximum daily temperature increase outpacing the mean warming rate, leading to more pronounced "unprecedented" extreme-temperature events as warming intensifies.

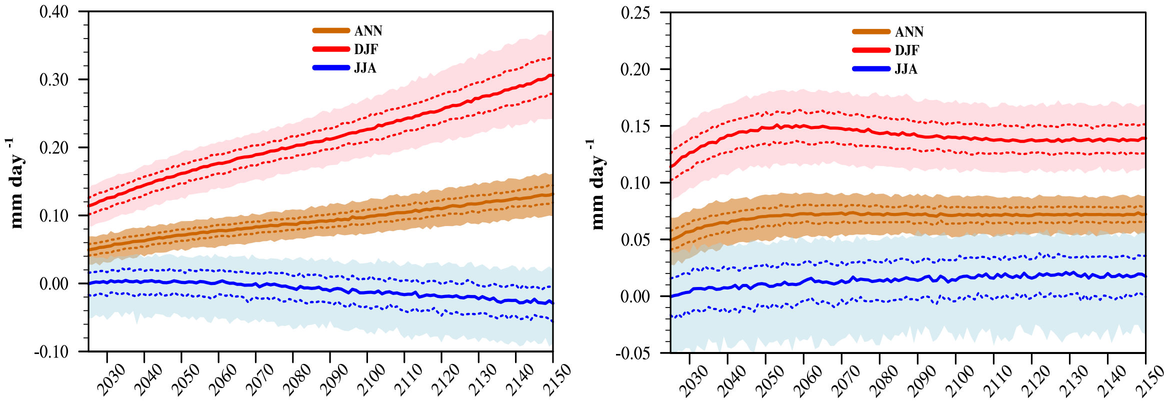

Figure 22. Projections for *Current Trends* (left) and *Accelerated Actions* (right) showing the range of 11,200 possible outcomes in precipitation change (relative to the 1861-1880 mean) averaged over Europe. See note above for more details.

Table 6. Summary of results for surface-air temperature change averaged over major continental regions. Units are in ˚C.

		Year	5th	25th	median	75th	95th	5th	25th	median	75th	95th	5th	25th	median	75th	95th
Annual					Africa					Asia					Europe		
	CT	2025	1.35	1.51	1.64	1.75	1.91	1.52	1.70	1.84	1.98	2.15	1.35	1.55	1.67	1.81	1.98
		2050	1.81	2.04	2.20	2.35	2.61	2.10	2.31	2.51	2.67	2.94	1.89	2.09	2.27	2.40	2.67
		2075	2.22	2.49	2.71	2.92	3.23	2.56	2.85	3.08	3.29	3.62	2.28	2.57	2.77	2.96	3.26
		2100	2.59	2.99	3.24	3.50	3.92	2.98	3.42	3.71	3.99	4.48	2.72	3.09	3.36	3.63	4.03
		2125	3.08	3.52	3.82	4.16	4.66	3.63	4.07	4.42	4.73	5.33	3.32	3.69	4.01	4.27	4.79
		2150	3.52	4.05	4.39	4.76	5.35	4.13	4.72	5.04	5.47	6.02	3.74	4.29	4.59	4.97	5.44
	AA	2025	1.35	1.51	1.64	1.75	1.91	1.52	1.70	1.84	1.98	2.15	1.35	1.55	1.67	1.81	1.98
		2050	1.63	1.82	1.99	2.12	2.35	1.87	2.08	2.26	2.42	2.65	1.68	1.86	2.02	2.18	2.41
		2075	1.55	1.76	1.90	2.07	2.32	1.76	2.01	2.15	2.31	2.56	1.58	1.80	1.94	2.09	2.28
		2100	1.44	1.67	1.81	1.96	2.20	1.68	1.89	2.04	2.21	2.46	1.51	1.70	1.86	2.00	2.25
		2125	1.44	1.62	1.76	1.92	2.18	1.65	1.85	2.00	2.16	2.44	1.48	1.65	1.80	1.94	2.23
		2150	1.43	1.64	1.78	1.95	2.20	1.65	1.86	2.01	2.19	2.42	1.47	1.68	1.80	1.98	2.17
					North America					Oceania					South America		
	CT	2025	1.60	1.79	1.93	2.08	2.25	1.14	1.29	1.42	1.53	1.70	1.23	1.40	1.52	1.63	1.80
		2050	2.22	2.44	2.64	2.80	3.07	1.52	1.76	1.90	2.07	2.34	1.65	1.86	2.02	2.18	2.45
		2075	2.69	2.99	3.23	3.45	3.77	1.84	2.15	2.39	2.60	2.94	1.98	2.28	2.50	2.73	3.05
		2100	3.15	3.61	3.91	4.20	4.68	2.22	2.62	2.87	3.13	3.60	2.38	2.76	3.02	3.26	3.72
		2125	3.84	4.28	4.66	4.97	5.59	2.65	3.09	3.41	3.74	4.26	2.78	3.24	3.55	3.88	4.41
		2150	4.35	4.97	5.31	5.76	6.31	3.02	3.58	3.96	4.34	4.95	3.21	3.74	4.10	4.49	5.09
	AA	2025	1.60	1.79	1.93	2.08	2.25	1.14	1.29	1.42	1.53	1.70	1.23	1.40	1.52	1.63	1.80
		2050	1.96	2.18	2.36	2.52	2.75	1.36	1.57	1.71	1.86	2.11	1.46	1.67	1.82	1.96	2.20
		2075	1.86	2.09	2.26	2.41	2.66	1.28	1.52	1.66	1.85	2.16	1.39	1.62	1.76	1.93	2.23
		2100	1.77	1.97	2.14	2.30	2.56	1.22	1.44	1.59	1.77	2.07	1.30	1.54	1.67	1.85	2.12
		2125	1.73	1.93	2.08	2.24	2.54	1.21	1.41	1.56	1.73	2.06	1.29	1.49	1.64	1.81	2.12
		2150	1.72	1.95	2.09	2.27	2.51	1.21	1.41	1.57	1.76	2.03	1.31	1.51	1.65	1.83	2.10
December-January-February					Africa					Asia					Europe		
	CT	2025	1.27	1.44	1.55	1.67	1.81	1.70	1.93	2.08	2.23	2.40	1.62	1.83	1.97	2.11	2.28
		2050	1.73	1.92	2.08	2.21	2.47	2.34	2.60	2.81	2.96	3.23	2.23	2.45	2.63	2.77	2.98
		2075	2.08	2.35	2.55	2.75	3.04	2.83	3.17	3.42	3.63	3.98	2.67	2.96	3.18	3.36	3.67
		2100	2.46	2.82	3.06	3.30	3.70	3.32	3.78	4.09	4.41	4.85	3.12	3.52	3.78	4.05	4.43
		2125	2.90	3.33	3.63	3.90	4.37	3.95	4.46	4.85	5.19	5.73	3.69	4.13	4.45	4.73	5.19
		2150	3.31	3.82	4.15	4.49	5.04	4.48	5.14	5.54	5.93	6.59	4.15	4.73	5.05	5.37	5.92
	AA	2025	1.27	1.44	1.55	1.67	1.81	1.70	1.93	2.08	2.23	2.40	1.62	1.83	1.97	2.11	2.28
		2050	1.55	1.73	1.87	2.00	2.23	2.10	2.34	2.54	2.68	2.95	2.00	2.21	2.39	2.52	2.73
		2075	1.48	1.67	1.81	1.97	2.20	2.04	2.27	2.45	2.63	2.88	1.95	2.15	2.32	2.46	2.67
		2100	1.38	1.58	1.72	1.87	2.08	1.91	2.18	2.31	2.50	2.77	1.84	2.07	2.20	2.36	2.58
		2125	1.35	1.54	1.68	1.83	2.06	1.88	2.12	2.27	2.43	2.69	1.82	2.02	2.15	2.29	2.53
		2150	1.38	1.55	1.68	1.84	2.08	1.90	2.11	2.26	2.44	2.71	1.83	2.03	2.15	2.31	2.53
					North America					Oceania					South America		
	CT	2025	1.98	2.22	2.40	2.56	2.77	1.07	1.23	1.36	1.48	1.64	1.14	1.30	1.41	1.53	1.69
		2050	2.71	3.01	3.23	3.41	3.70	1.44	1.67	1.83	1.99	2.27	1.52	1.73	1.88	2.04	2.30
		2075	3.27	3.63	3.93	4.17	4.55	1.76	2.06	2.29	2.51	2.86	1.85	2.13	2.33	2.55	2.85
		2100	3.84	4.37	4.70	5.05	5.54	2.14	2.49	2.76	3.01	3.46	2.18	2.55	2.80	3.03	3.45
		2125	4.57	5.13	5.56	5.95	6.56	2.50	2.96	3.27	3.57	4.09	2.56	3.01	3.31	3.59	4.09
		2150	5.17	5.92	6.36	6.80	7.58	2.88	3.42	3.79	4.17	4.76	3.01	3.48	3.81	4.16	4.71
	AA	2025	1.98	2.22	2.40	2.56	2.77	1.07	1.23	1.36	1.48	1.64	1.14	1.30	1.41	1.53	1.69
		2050	2.42	2.69	2.91	3.07	3.36	1.27	1.49	1.64	1.78	2.03	1.34	1.56	1.69	1.83	2.08
		2075	2.36	2.61	2.81	3.00	3.27	1.21	1.47	1.61	1.79	2.09	1.30	1.51	1.64	1.82	2.09
		2100	2.21	2.50	2.65	2.86	3.15	1.16	1.37	1.53	1.71	2.00	1.22	1.43	1.56	1.73	1.99
		2125	2.17	2.44	2.60	2.77	3.09	1.13	1.34	1.50	1.67	1.98	1.20	1.39	1.53	1.69	1.94
		2150	2.19	2.43	2.59	2.79	3.09	1.14	1.35	1.52	1.70	1.97	1.20	1.40	1.54	1.71	1.96
June-July-August					Africa					Asia					Europe		
	CT	2025	1.38	1.56	1.69	1.82	1.98	1.18	1.40	1.55	1.71	1.99	0.97	1.23	1.39	1.61	2.05
		2050	1.89	2.14	2.31	2.48	2.75	1.72	1.99	2.16	2.37	2.66	1.47	1.76	1.94	2.17	2.62
		2075	2.32	2.62	2.85	3.06	3.40	2.17	2.48	2.68	2.91	3.25	1.86	2.19	2.44	2.69	3.13
		2100	2.73	3.13	3.41	3.69	4.14	2.59	3.00	3.24	3.55	4.06	2.31	2.72	3.00	3.32	3.89
		2125	3.29	3.71	4.02	4.38	4.91	3.20	3.61	3.93	4.21	4.80	2.90	3.35	3.66	4.01	4.64
		2150	3.77	4.28	4.63	5.02	5.62	3.63	4.15	4.51	4.97	5.47	3.35	3.87	4.24	4.67	5.27
	AA	2025	1.38	1.56	1.69	1.82	1.98	1.18	1.40	1.55	1.71	1.99	0.97	1.23	1.39	1.61	2.05
		2050	1.70	1.92	2.08	2.24	2.48	1.52	1.77	1.94	2.12	2.49	1.26	1.52	1.71	1.93	2.41
		2075	1.62	1.85	2.01	2.17	2.45	1.42	1.69	1.84	2.01	2.27	1.17	1.43	1.63	1.81	2.18
		2100	1.52	1.74	1.89	2.08	2.33	1.33	1.57	1.75	1.93	2.30	1.07	1.37	1.55	1.76	2.25
		2125	1.49	1.70	1.87	2.05	2.31	1.32	1.53	1.70	1.89	2.23	1.07	1.29	1.50	1.71	2.11
		2150	1.51	1.73	1.87	2.06	2.31	1.29	1.55	1.73	1.93	2.20	1.03	1.33	1.53	1.74	2.13
					North America					Oceania					South America		
	CT	2025	1.15	1.36	1.51	1.69	1.95	1.14	1.29	1.40	1.52	1.68	1.26	1.42	1.55	1.67	1.82
		2050	1.64	1.92	2.09	2.30	2.63	1.35	1.56	1.71	1.85	2.10	1.67	1.90	2.08	2.23	2.52
		2075	2.07	2.40	2.59	2.83	3.20	1.29	1.52	1.66	1.84	2.14	2.05	2.34	2.57	2.79	3.14
		2100	2.51	2.90	3.16	3.48	3.94	1.23	1.44	1.59	1.77	2.05	2.44	2.82	3.09	3.35	3.82
		2125	3.09	3.49	3.81	4.13	4.70	1.20	1.41	1.56	1.73	2.04	2.88	3.34	3.64	3.99	4.53
		2150	3.52	4.04	4.41	4.83	5.31	1.21	1.41	1.56	1.76	2.04	3.33	3.87	4.21	4.63	5.23
	AA	2025	1.15	1.36	1.51	1.69	1.95	1.14	1.29	1.40	1.52	1.68	1.26	1.42	1.55	1.67	1.82
		2050	1.44	1.69	1.86	2.05	2.44	1.35	1.56	1.71	1.85	2.10	1.49	1.72	1.86	2.02	2.26
		2075	1.33	1.61	1.76	1.94	2.23	1.29	1.52	1.66	1.84	2.14	1.44	1.65	1.80	1.99	2.27
		2100	1.28	1.50	1.68	1.87	2.21	1.23	1.44	1.59	1.77	2.05	1.34	1.57	1.71	1.90	2.18
		2125	1.24	1.45	1.63	1.83	2.17	1.20	1.41	1.56	1.73	2.04	1.33	1.53	1.68	1.87	2.16
		2150	1.22	1.47	1.67	1.85	2.12	1.21	1.41	1.56	1.76	2.04	1.34	1.54	1.69	1.89	2.18

Table 7. Summary of results for precipitation change averaged over major continental regions. Units are in mm/year.

		Year	5th	25th	median	75th	95th	5th	25th	median	75th	95th	5th	25th	median	75th	95th
Annual			Africa					Asia					Europe				
	CT	2025	0.02	0.03	0.04	0.05	0.06	0.06	0.08	0.10	0.11	0.13	0.03	0.04	0.05	0.06	0.07
		2050	0.04	0.05	0.06	0.07	0.08	0.11	0.13	0.15	0.17	0.19	0.05	0.06	0.07	0.08	0.09
		2075	0.05	0.06	0.07	0.08	0.10	0.15	0.17	0.19	0.21	0.23	0.06	0.08	0.08	0.09	0.11
		2100	0.06	0.08	0.09	0.10	0.13	0.19	0.22	0.24	0.26	0.30	0.07	0.09	0.10	0.11	0.12
		2125	0.07	0.10	0.11	0.13	0.16	0.23	0.27	0.29	0.32	0.37	0.08	0.10	0.11	0.13	0.14
		2150	0.09	0.12	0.13	0.16	0.20	0.27	0.31	0.35	0.38	0.43	0.10	0.12	0.13	0.14	0.16
	AA	2025	0.02	0.03	0.04	0.05	0.06	0.06	0.08	0.10	0.11	0.13	0.03	0.04	0.05	0.06	0.07
		2050	0.03	0.05	0.05	0.06	0.07	0.10	0.12	0.14	0.15	0.17	0.05	0.06	0.07	0.08	0.09
		2075	0.04	0.05	0.06	0.06	0.08	0.10	0.13	0.14	0.15	0.17	0.05	0.07	0.07	0.08	0.09
		2100	0.03	0.05	0.05	0.06	0.07	0.10	0.12	0.13	0.15	0.17	0.05	0.06	0.07	0.08	0.09
		2125	0.04	0.05	0.05	0.06	0.07	0.10	0.12	0.13	0.14	0.16	0.05	0.07	0.07	0.08	0.09
		2150	0.03	0.05	0.05	0.06	0.07	0.10	0.12	0.13	0.15	0.16	0.06	0.07	0.07	0.08	0.09
			North America					Oceania					South America				
	CT	2025	0.03	0.05	0.06	0.07	0.08	-0.01	0.02	0.04	0.05	0.08	-0.02	0.00	0.02	0.05	0.08
		2050	0.07	0.09	0.10	0.11	0.12	0.00	0.03	0.05	0.08	0.11	-0.03	0.00	0.02	0.05	0.09
		2075	0.10	0.11	0.13	0.14	0.15	0.01	0.05	0.08	0.11	0.15	-0.03	0.01	0.03	0.07	0.11
		2100	0.12	0.14	0.16	0.17	0.19	0.03	0.08	0.10	0.14	0.20	-0.02	0.02	0.04	0.08	0.12
		2125	0.15	0.18	0.19	0.21	0.25	0.05	0.10	0.14	0.18	0.25	-0.02	0.02	0.05	0.09	0.15
		2150	0.18	0.21	0.23	0.26	0.29	0.08	0.14	0.19	0.23	0.32	-0.02	0.04	0.07	0.12	0.19
	AA	2025	0.03	0.05	0.06	0.07	0.08	-0.01	0.02	0.04	0.05	0.08	-0.02	0.00	0.02	0.05	0.08
		2050	0.07	0.08	0.09	0.10	0.11	0.00	0.03	0.05	0.07	0.10	-0.02	0.01	0.03	0.05	0.09
		2075	0.07	0.08	0.09	0.10	0.11	0.00	0.04	0.06	0.08	0.12	-0.01	0.02	0.04	0.07	0.11
		2100	0.07	0.08	0.09	0.10	0.11	0.01	0.04	0.06	0.08	0.12	0.00	0.02	0.04	0.07	0.11
		2125	0.07	0.08	0.09	0.09	0.11	0.01	0.03	0.06	0.09	0.12	-0.01	0.02	0.05	0.08	0.12
		2150	0.07	0.08	0.09	0.10	0.10	0.01	0.04	0.06	0.08	0.12	0.00	0.02	0.05	0.08	0.12
December-January-February			Africa					Asia					Europe				
	CT	2025	0.00	0.02	0.03	0.04	0.06	0.06	0.08	0.09	0.10	0.11	0.08	0.10	0.11	0.12	0.14
		2050	0.00	0.03	0.04	0.06	0.08	0.10	0.11	0.13	0.14	0.15	0.12	0.15	0.16	0.17	0.19
		2075	0.01	0.04	0.06	0.08	0.11	0.12	0.14	0.16	0.17	0.20	0.16	0.18	0.19	0.21	0.23
		2100	0.03	0.05	0.07	0.10	0.13	0.15	0.18	0.20	0.22	0.25	0.18	0.21	0.22	0.24	0.27
		2125	0.03	0.07	0.09	0.12	0.17	0.18	0.22	0.24	0.26	0.30	0.21	0.24	0.26	0.28	0.32
		2150	0.05	0.09	0.11	0.15	0.20	0.22	0.26	0.28	0.31	0.35	0.24	0.28	0.31	0.33	0.37
	AA	2025	0.00	0.02	0.03	0.04	0.06	0.06	0.08	0.09	0.10	0.11	0.08	0.10	0.11	0.12	0.14
		2050	0.00	0.03	0.04	0.05	0.08	0.09	0.10	0.12	0.13	0.14	0.11	0.13	0.15	0.16	0.18
		2075	0.01	0.03	0.05	0.07	0.09	0.09	0.10	0.11	0.13	0.14	0.11	0.13	0.15	0.16	0.18
		2100	0.01	0.03	0.05	0.06	0.09	0.09	0.10	0.11	0.12	0.13	0.11	0.13	0.14	0.15	0.17
		2125	0.01	0.03	0.05	0.07	0.09	0.08	0.10	0.11	0.12	0.13	0.11	0.13	0.14	0.15	0.17
		2150	0.01	0.03	0.05	0.06	0.09	0.09	0.10	0.11	0.12	0.13	0.11	0.13	0.14	0.15	0.17
			North America					Oceania					South America				
	CT	2025	0.07	0.08	0.09	0.10	0.12	-0.02	0.03	0.06	0.09	0.13	-0.02	0.03	0.07	0.10	0.15
		2050	0.11	0.13	0.14	0.15	0.17	0.00	0.05	0.09	0.12	0.18	-0.01	0.04	0.08	0.12	0.18
		2075	0.14	0.16	0.18	0.20	0.22	0.03	0.08	0.12	0.17	0.23	-0.01	0.06	0.11	0.15	0.22
		2100	0.17	0.20	0.22	0.24	0.27	0.06	0.12	0.16	0.21	0.30	0.02	0.08	0.13	0.18	0.27
		2125	0.21	0.24	0.27	0.29	0.34	0.09	0.15	0.21	0.27	0.38	0.02	0.10	0.16	0.23	0.34
		2150	0.25	0.29	0.32	0.35	0.40	0.11	0.21	0.27	0.35	0.48	0.05	0.14	0.20	0.27	0.40
	AA	2025	0.07	0.08	0.09	0.10	0.12	-0.02	0.03	0.06	0.09	0.13	-0.02	0.03	0.07	0.10	0.15
		2050	0.10	0.12	0.13	0.14	0.16	-0.01	0.04	0.08	0.11	0.17	-0.01	0.04	0.08	0.12	0.18
		2075	0.10	0.12	0.13	0.14	0.16	0.01	0.06	0.10	0.14	0.19	0.00	0.06	0.10	0.15	0.21
		2100	0.09	0.11	0.12	0.13	0.15	0.02	0.06	0.10	0.14	0.20	0.01	0.06	0.10	0.15	0.23
		2125	0.10	0.11	0.12	0.13	0.15	0.01	0.07	0.10	0.14	0.19	0.01	0.06	0.10	0.15	0.23
		2150	0.10	0.11	0.12	0.13	0.15	0.01	0.06	0.10	0.14	0.20	0.01	0.06	0.10	0.15	0.22
June-July-August			Africa					Asia					Europe				
	CT	2025	0.01	0.03	0.05	0.06	0.08	0.01	0.07	0.10	0.14	0.18	-0.05	-0.02	0.00	0.02	0.04
		2050	0.03	0.05	0.06	0.08	0.10	0.06	0.13	0.17	0.21	0.25	-0.05	-0.02	0.00	0.02	0.04
		2075	0.04	0.07	0.08	0.09	0.11	0.13	0.18	0.22	0.26	0.31	-0.06	-0.02	0.00	0.02	0.04
		2100	0.06	0.08	0.09	0.11	0.13	0.16	0.24	0.28	0.32	0.38	-0.07	-0.03	-0.01	0.01	0.03
		2125	0.08	0.10	0.12	0.13	0.15	0.22	0.28	0.33	0.38	0.46	-0.08	-0.04	-0.02	0.00	0.02
		2150	0.09	0.12	0.14	0.15	0.18	0.25	0.34	0.40	0.45	0.53	-0.09	-0.06	-0.03	0.00	0.02
	AA	2025	0.01	0.03	0.05	0.06	0.08	0.00	0.07	0.10	0.14	0.19	-0.05	-0.02	0.00	0.02	0.04
		2050	0.03	0.05	0.06	0.08	0.10	0.05	0.11	0.15	0.19	0.24	-0.04	-0.01	0.01	0.03	0.05
		2075	0.02	0.05	0.06	0.07	0.09	0.07	0.12	0.16	0.20	0.25	-0.03	0.00	0.02	0.03	0.05
		2100	0.02	0.04	0.05	0.07	0.08	0.07	0.13	0.16	0.19	0.23	-0.04	0.00	0.01	0.03	0.05
		2125	0.03	0.04	0.05	0.07	0.09	0.05	0.12	0.15	0.18	0.24	-0.03	0.00	0.02	0.03	0.05
		2150	0.02	0.04	0.06	0.07	0.09	0.06	0.12	0.16	0.18	0.23	-0.03	0.00	0.02	0.04	0.06
			North America					Oceania					South America				
	CT	2025	-0.06	-0.03	-0.01	0.01	0.03	-0.03	0.00	0.03	0.05	0.08	-0.02	0.02	0.04	0.07	0.10
		2050	-0.05	-0.01	0.00	0.02	0.05	-0.04	0.00	0.03	0.06	0.10	-0.02	0.02	0.04	0.06	0.10
		2075	-0.04	-0.01	0.01	0.03	0.05	-0.02	0.02	0.06	0.09	0.13	-0.01	0.02	0.05	0.08	0.11
		2100	-0.03	0.00	0.01	0.03	0.05	0.00	0.05	0.07	0.11	0.16	-0.01	0.03	0.06	0.08	0.12
		2125	-0.03	0.00	0.02	0.04	0.06	0.01	0.06	0.10	0.14	0.21	0.00	0.04	0.07	0.10	0.14
		2150	-0.03	0.01	0.03	0.05	0.08	0.04	0.10	0.14	0.18	0.26	0.01	0.05	0.08	0.12	0.17
	AA	2025	-0.06	-0.03	-0.01	0.01	0.03	-0.03	0.00	0.03	0.05	0.08	-0.02	0.02	0.04	0.07	0.10
		2050	-0.04	-0.01	0.01	0.03	0.05	-0.03	0.01	0.03	0.06	0.10	-0.02	0.02	0.04	0.07	0.10
		2075	-0.03	0.00	0.02	0.03	0.05	-0.02	0.02	0.04	0.07	0.11	-0.01	0.03	0.05	0.07	0.11
		2100	-0.03	0.00	0.02	0.03	0.06	-0.02	0.01	0.04	0.07	0.11	-0.02	0.02	0.05	0.07	0.11
		2125	-0.03	0.00	0.02	0.03	0.05	-0.03	0.01	0.04	0.07	0.11	-0.01	0.03	0.05	0.07	0.11
		2150	-0.03	0.00	0.02	0.03	0.05	-0.03	0.01	0.04	0.07	0.11	-0.01	0.02	0.05	0.07	0.10

Box 4.

Net-zero emissions by 2050: Is the world willing to pay more to lock in its long-term climate goal?

Context

Achieving the Paris Agreement's long-term goal of capping global warming at 1.5°C, ideally by the end of this century, means that the planet's total greenhouse gas emissions will eventually need to decline to net-zero: the sum total of greenhouse gases released into and removed from the atmosphere must be zero. To that end, about 140 countries have announced or are considering net-zero emissions targets, most with a target date of 2050.

Despite the focus on net-zero emissions by 2050, there is nothing magical about the 2050 target. There are countless emissions pathways that could be consistent with the 1.5°C goal, including those that do not achieve net-zero global emissions in this century. In the latest IPCC Assessment Report (AR6), while all of the scenarios that limit warming to 1.5°C (with at least a 50% chance and no or limited overshoot) reach net-zero CO_2 emissions by 2070, only half of the pathways reach net-zero greenhouse gas (GHG) emissions at any point during the second half of the 21st century (IPCC, 2022a).

So, while a 2050 net-zero target is helpful for setting the world on the right path, it is not a requirement for meeting the 1.5°C goal. Importantly, there are different energy, environmental and economic implications of meeting a global net-zero-emissions target by 2050 versus choosing other pathways of limiting global warming to 1.5°C.

Key Findings

To explore these implications, we have applied our coupled human/Earth-system model to a 1.5°C scenario and a set of net-zero-by-2050 scenarios in which the coverage of net-zero targets (applying to all countries vs. just the U.S. and E.U.) and participation in international emissions trading were varied (Morris *et al.*, 2023). We find that for all scenarios, meeting such stringent targets requires a two-pronged approach. This approach combines the deployment of (1) zero-to-low-carbon technologies to reduce released emissions and (2) "negative emissions" technologies/processes to offset persisting released emissions that are difficult to eliminate. The former include wind, solar, hydro, bioenergy, nuclear, carbon capture and storage (CCS), and hydrogen; the latter include bioenergy with CCS (BECCS), direct air capture with carbon storage, and nature-based solutions such as refor-

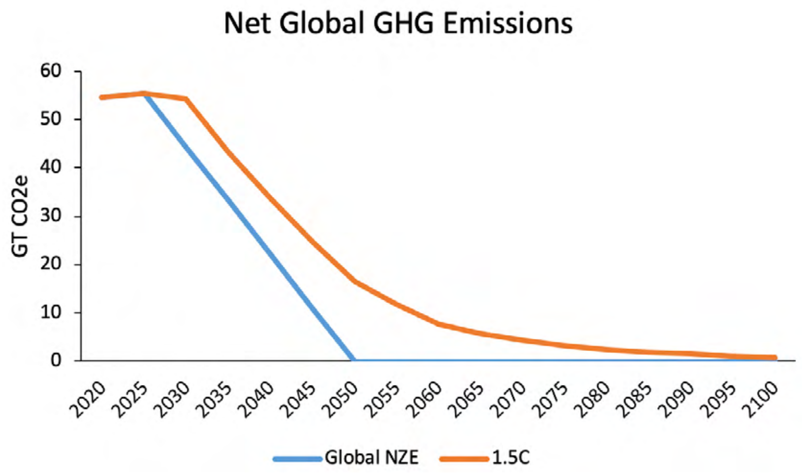

Figure 23. Net global GHG emissions pathways under the Global NZE (net-zero emissions) by 2050 scenario and an alternative 1.5°C pathway.

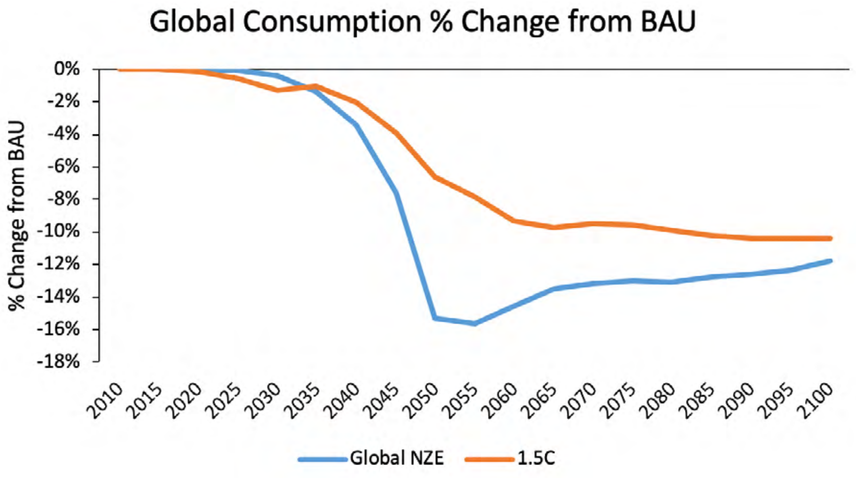

Figure 24. Global consumption as percentage change from Business as Usual (BAU) under the Global NZE by 2050 scenario and the 1.5°C scenario.

estation, afforestation and agricultural practices that sequester carbon in soils.

In all scenarios, we find that the policies are met by utilizing large amounts of negative emissions—from afforestation in the short term and BECCS in the long term. The negative emissions offset ongoing emissions from hard-to-abate sectors such as iron, steel, cement, chemicals, trucking, aviation and agriculture. In particular, they enable the continued use of oil as a fuel source for commercial transportation.

When every nation achieves net-zero emissions by 2050, a more rapid scale-up of BECCS becomes necessary, incurring much higher costs at mid-century (more than twice as high) than if some countries are allowed to continue producing some emissions in the second half of the century. In the latter scenario, the costs for those countries that do meet net-zero targets are reduced if they participate in emissions trading with the rest of the world and utilize international credits. Additional cost savings could be achieved through the emergence of novel technological and electrification options to reduce emissions in hard-to-abate industries.

At the same time, when all countries achieve net-zero emissions by 2050, the average global surface temperature slightly overshoots 1.5°C in 2050 but falls to 1.2°C by 2100, making it highly likely (with a 96% chance, accounting for uncertainty in the climate system) that the 1.5°C target is met. By comparison, global mitigation with only some countries achieving the net-zero-emissions-by-2050 target can result in a 50% chance of limiting temperature to 1.5°C by 2100, but with an upper limit on temperature as high as 1.85°C.

Implications

This research shows a tradeoff between policy costs and ensuring that global warming does not exceed 1.5°C. Achieving global net-zero emissions by 2050 is not necessarily required in order to keep global warming at or below 1.5°C, and would add considerable policy costs, especially at mid-century. However, meeting the 2050 deadline—ideally utilizing international emissions trading to reduce policy costs—would essentially guarantee the achievement of the 1.5°C target.

More Information

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Table 8. Summary of Temperature Results from Global NZE and 1.5C scenarios.

Scenario	Median in 2100 (2091-2100)	Likelihood below 1.5C in 2100 (2091-2100)	Median Peak	Likelihood Peak below 1.5C during Century
Global NZE	1.2C	96%	1.54	43%
1.5C	1.5C	50%	1.57	37%

Scenario	Percentiles for 2100 (2091-2100) Temperature						
	5%	17%	33%	50%	66%	83%	95%
Global NZE	0.97	1.05	1.13	1.20	1.26	1.34	1.47
1.5C	1.23	1.33	1.42	1.50	1.57	1.68	1.85

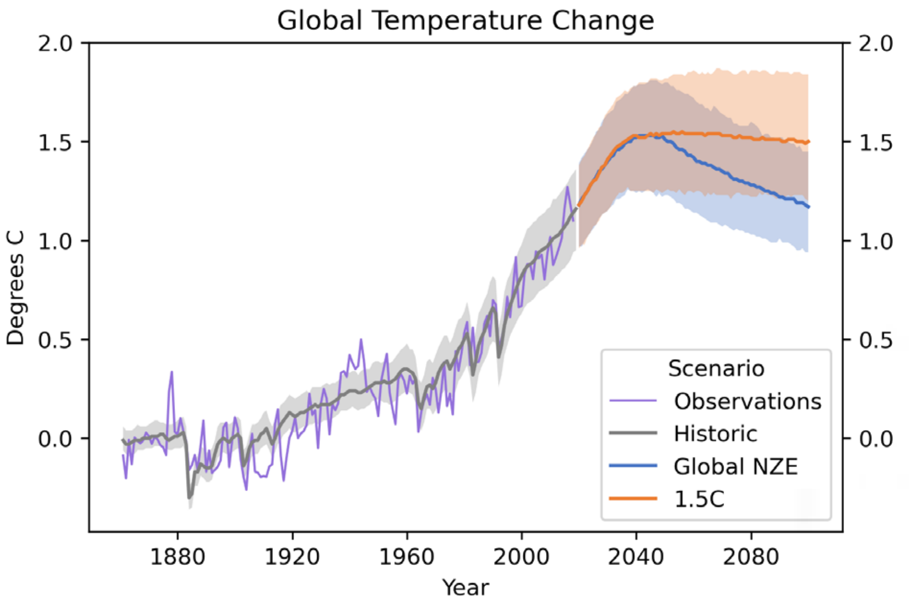

Figure 25. Global surface air temperature increases relative to pre-industrial levels under the Global NZE by 2050 scenario and the 1.5°C scenarios, along with the historical period and observations. Shaded areas reflect the 90% bounds.

Transition Risk

Context

Climate change poses transition risks that arise from shifts in political, technological, social and economic landscapes that are likely to occur during the transition to a low-carbon economy. The pace of transformation could be uneven, and there are substantial uncertainties in how future technologies, policies and regulations, national stability, economic growth and other aspects of human development will evolve. With recently increased geopolitical tensions, these uncertainties are even greater. Transition risks affect all economic activities, since virtually every sector is directly responsible for some greenhouse gas emissions, and the value chains for all sectors involve major emissions sources. Assessing these risks accurately is a challenging task that requires a comprehensive understanding of the underlying drivers of the climate and the transmission channels of climate impacts through the economy.

Recent Findings

Transition risks depend on the likelihood of particular policies getting enacted as well as their stringency. For example, a rapid transition away from fossil fuels results in stranded assets, where earnings from fossil-fuel assets and resources are reduced or eliminated due to lower prices, more fuels are left in the ground, and restrictions are imposed on certain types of power plants (e.g., coal-based). On the other hand, slow decarbonization may negatively affect deployment of technologies that require high carbon prices.

To better understand climate-related risks to the economy and the financial system, we collaborated with the Bank of Canada to develop a set of Canada-relevant climate transition scenarios that explore pathways consistent with achieving certain climate targets. These scenarios vary in terms of two key drivers of climate transition risk: (1) the ambition and timing of climate policy and (2) the pace of technological change and availability of advanced technologies. The analysis, reported in Chen *et al* (2022), illustrated the important sectoral restructuring the Canadian and global economies may need to undertake to meet climate targets. It also showed that every sector contributes to the transition and that financial impacts vary across sectors. These impacts depend on how different sectors are impacted by emissions and capital expenditures costs, and on how the demand for their products is affected by the decarbonization of economies. The scenarios also shed light on the risks of significant macroeconomic impacts, particularly for commodity-exporting countries like Canada. The economic impacts for Canada are driven mostly by declines in global prices of commodities rather than by domestic policy decisions.

Another factor to consider in assessing Canada's transition risk stems from the Paris Agreement, in which Nationally Determined Contributions (NDCs) create variations in climate policy across countries. One implication is a potential erosion of international competitiveness of sectors in countries implementing more stringent climate actions. Border Carbon Adjustments (BCAs) have been proposed as a mechanism to mitigate the drawbacks of global policy fragmentation. For example, the European Union has introduced its carbon border adjustment mechanism (EU CBAM) that covers several sectors (cement, iron and steel, aluminum, fertilizers, electricity and hydrogen) initially and likely more in the future. We explored the impacts of Canada's response to the EU actions by imposing its own BCA (Chen *et al,* 2023). BCAs may take the form of an import charge and sometimes rebates on exports. **Figure 26** illustrates the sectoral financial impacts on sectors in Canada for the different BCA design features studied. In general, sectors for which imports have a higher share in domestic supply (cement, iron and steel, other energy-intensive sectors, other manufacturing sectors, and food) gain more domestic market share under BCAs, but net-exporting sectors such as fossil-fuel sectors in Canada are worse off.

Transition risk assessment can be done for a particular investment type, company, industry or country. For suggesting company-specific emissions reduction targets, numerous initiatives use science-based global CO_2 emission trajectories aligned with particular climate goals. While assigning a global emissions trajectory at the company level may provide a rough indication of the required mitigation effort, it does not adequately represent company-specific market dynamics. In our joint work with Amundi, we explored a methodology for quantifying climate-related transition impacts on energy-intensive companies (Le Guenedal *et al.*, 2023). While in this Outlook we do not assess the impacts of climate risk on a particular investment portfolio, our collaboration with Amundi does illustrate how a set of scenarios can be used to evaluate particular investment decisions.

Implications

Transition risk associated with resource rents may be unavoidable, but increasing losses can be avoided by not investing further in developing carbon-intensive resources. Specific investment portfolios can be further explored for an expanded set of policy and technology scenarios for metrics such as energy prices, technology deployment levels, sectoral production levels and stringency of government support. Moreover, we argue that where possible, investors should not rely on just two or three scenarios but rather explore a comprehensive set of scenarios that consider uncertainty in socio-economic and climate inputs—all to obtain information on the likelihood of various outcomes. Our consistent framework for addressing uncertainty in coupled human-Earth system models enables decision-makers to account for both physical and socio-economic components of climate risk and to quantify uncertainty in assessing transition risk (Morris *et al.*, 2021 and Morris *et al.*, 2022).

More Information

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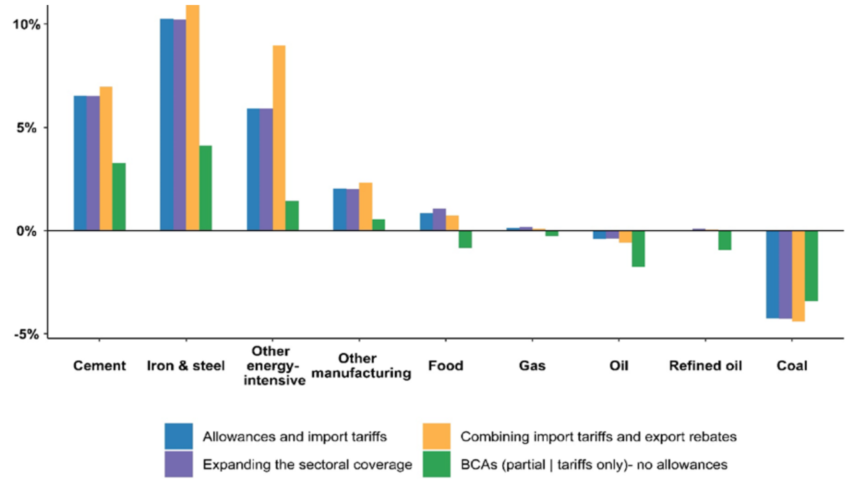

Figure 26. Cumulative (2020-2030) sectoral financial impacts in Canada (as % change relative to the uncoordinated scenario) from imposition of border carbon adjustment mechanisms. Source: Chen *et al* (2023).

Exploring Climate Impacts on the Economy

Context

The most recent report of Working Group II of the Intergovernmental Panel on Climate Change (IPCC, 2022c) provides the most comprehensive assessment of the risks we face from climate change. However, the report stops short of attempting to sum up the climate impacts in economic terms or to fully assess feedbacks on the economy, reflecting the difficulty of this task and the tremendous uncertainties inherent in doing so. A variety of approaches have been employed to assess aggregate climate impacts (Rose *et al.*, 2017; Gillingham *et al.*, 2018; Hartin *et al.*, 2023) including efforts to evaluate impacts at very fine geographic resolution for various human activities likely to be affected by climate change (Hsiang *et al.*, 2017).

There are two leading approaches for evaluating climate impacts (Blanc & Reilly, 2017). One approach is to statistically estimate the response to weather for different human activities using historical data. The Climate Impact Lab has mounted a major effort to develop such response functions for ~24,000 administrative units (counties or their equivalent) across the globe. These can be aggregated for input into a global economic model to assess economic impacts at regional and global levels. A second approach is to develop mechanistic or process models of response to weather. Examples include crop models that operate on highly resolved time steps, or water models that explicitly model changes in water runoff and its impact on flooding, availability of irrigation water, or hydroelectric power production. While the process-model approach can be computationally intensive, recent work (Takakura *et al.*, 2021) developed simpler response functions from such assessments that make it possible to input these impacts into a model of the world economy to assess aggregate economic impacts. The activities evaluated in these different studies include labor productivity, heat-related mortality, agricultural productivity, cooling/heating demand, hydropower production, thermal power cooling, fluvial flooding, coastal inundation, undernourishment, air quality, infrastructure and ecosystems.

A general finding from these studies is that one of the largest impacts on the aggregate economy is from climate impacts on labor. There are several channels by which climate can affect labor and, in turn, the economy. Workplace heat exposure can lead to labor-supply losses due to mortalities, medical expenditure increases due to mortalities and morbidity, lost working hours due to morbidity and heat-stress, and labor-productivity losses due to heat stress. Beyond heat, climate change can cause lost labor time due to disruptions from extreme events such as flooding, wildfires or hurricanes. However, due to insufficient data or methodological limitations, most studies include only a subset of these impact channels, often focusing on lost work hours or lost productivity due to heat (Zhao *et al.*, 2021).

Key Findings

While the majority of previous studies have fed climate impacts into relatively simple macroeconomic models, there is value in implementing these impacts in a multi-sector, economy-wide model like EPPA which can capture not only the direct economic implications of climate impacts, but also the implications of additional feedbacks and ripple effects throughout the economy. As a preliminary attempt to test how climate impacts may feedback on the economy in EPPA, we have used a measure of the climate effect on labor developed by the Climate Impact Lab (Rode *et al.*, 2022). That study estimated the impact of temperature on hours worked for each of the ~24,000 administrative units in the world, for two classes of labor—those in economic sectors directly exposed to outdoor temperatures (high-risk workers) and those in other sectors where labor is less exposed (low-risk workers). The study went to considerable lengths to represent uncertainty in these estimates, and to emphasize that effects can vary significantly for different administrative units, and thus caution is required when aggregating these impacts to large regions (as we have in EPPA).

We used the response functions for the Climate Impact Lab's ~24,000 administrative units (using only the median estimates) to calculate the climate impacts on labor for each unit based on temperature and GDP per capita projections from the Integrated Global System Modeling (IGSM) framework under our *Current Trends* and *Accelerated Actions* scenarios. We next aggregated those impacts to the EPPA model's 18 regions by taking a population-weighted average of the administrative units within each EPPA region (see **Figure 27**), and then imposed the regional impacts in EPPA under each scenario to find the economic implications of these climate feedbacks. As shown in **Figure 28**, some regions see decreases in labor due to temperature changes (such as India and the Middle East), while others see labor increases (such as Canada), and high-risk workers face non-linear labor impacts in response to temperature. In particular, there are temperature tipping points at which high-risk workers face exponential decreases in hours worked (Rode *et al.*, 2022).

Results show that under the *Current Trends* scenario, the aggregate global economic impact of climate feedbacks on labor is generally small through mid-century, but then grows rapidly through 2100 (**Figure 29**). Importantly, global average temperature in the *Current Trends* scenario continues to rise nearly linearly beyond 2100, so with labor losses increasing exponentially at high temperatures, economic impacts would grow significantly in the 22nd century. However, these impacts can be largely avoided through stronger climate-change mitigation efforts, with global impacts in 2100 declining from $1.2 trillion USD in the *Current Trends* scenario to $1 billion USD in the *Accelerated Actions* scenario. Importantly, the economic impact of this climate feedback varies significantly by region. Tropical regions generally face more negative impacts, while more temperate and colder regions can see positive impacts (**Table 9**). These results align with studies cited above for scenarios achieving similar temperature

Table 9. Regional changes in GDP due to climate impacts on labor in 2100 (in billion USD)

	Current Trends	Accelerated Actions
IND	-704	-98
MES	-304	-61
AFR	-152	-7
REA	-101	-14
BRA	-99	-19
ASI	-99	-25
LAM	-88	-12
MEX	-75	-23
USA	-50	65
IDZ	-44	4
ROE	-2	8
ANZ	1	4
RUS	16	-1
CAN	38	20
JPN	43	17
CHN	56	4
KOR	69	21
EUR	294	103

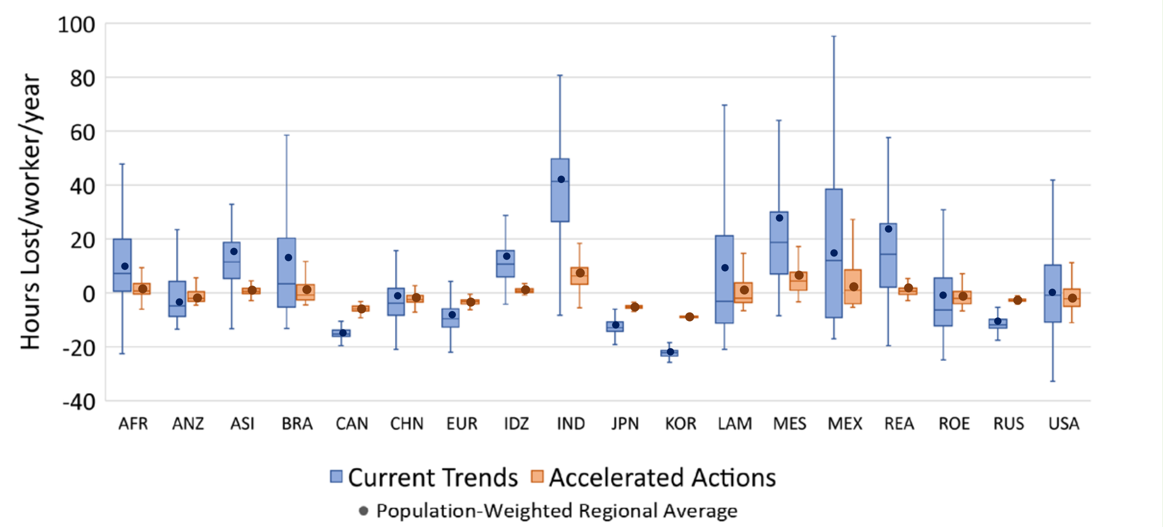

Figure 27. Direct impact of climate on labor of high-risk workers by region in 2100, in terms of hours of labor lost per worker per year (positive values = hours lost; negative values = hours gained). Box and whisker plots reflect the variation across the administrative units within an EPPA region. Points reflect the population-weighted average hours lost across administrative units in each EPPA region.

outcomes. In particular, for a temperature outcome similar to our *Current Trends* scenario, a recent study for the U.S. found mean climate-driven damages from labor in 2090 to be $51 billion USD (Hartin *et al.*, 2023), compared to our finding of $50 billion USD losses in 2100.

Implications

While this exercise is a valuable step toward accounting for climate feedbacks in an economy-wide model like EPPA, there are some important caveats and cautions.

First, climate impacts on labor are only one pathway by which climate change can affect the economy; many others can and should be quantified as well. While recent attempts to more comprehensively assess climate impacts are impressive, some additional impacts have not yet been developed for the entire world, such as effects on wildfires, air pollution and possible follow-on effects such as political instability and migration that could magnify economic costs. Second, even for a single climate impact, it is difficult to get a comprehensive assessment. For example, hours worked only captures part of the climate impact on labor productivity—effective work performed per hour may also be impacted, as well as the overall labor supply. Similarly, labor can be affected by climate impacts beyond those captured in our key findings above.

Third, direct climate impacts do not necessarily translate directly to economic impacts, suggesting the value of incorporating these impacts into a multi-sector economy-wide model which can capture additional feedbacks and responses to impacts. For example, as found in the

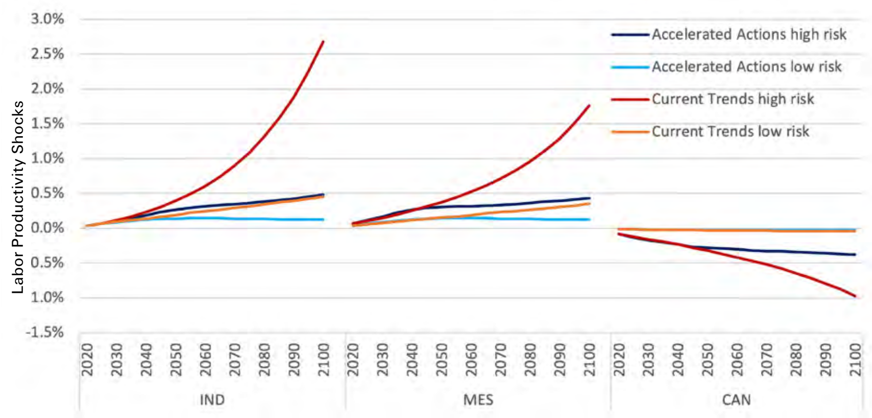

Figure 28. Labor productivity shocks for example regions (positive values = labor productivity decreases; negative values = labor productivity increases). Shocks are calculated as the hours lost per year/typical number of hours worked per year (which is assumed to be 1,500 hours- 6 hours per day for 250 days per year).

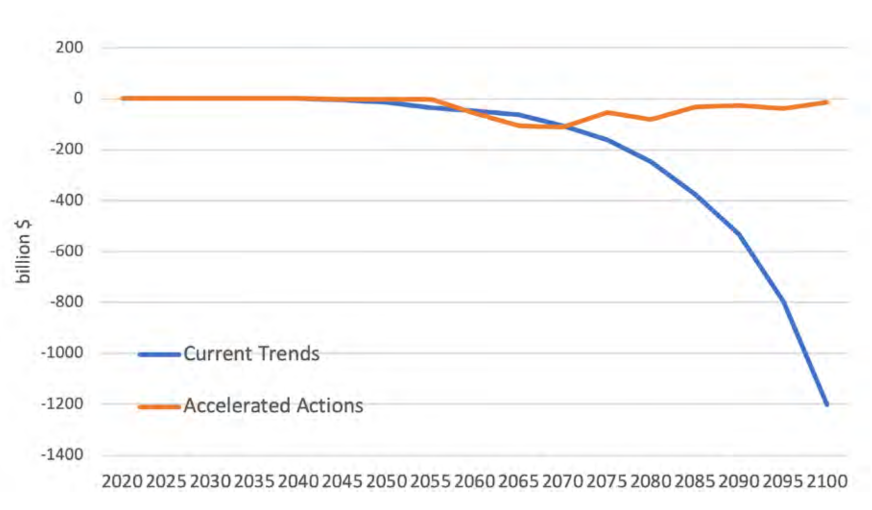

Figure 29. Global changes in GDP due to climate impacts on labor (in billion USD).

aforementioned studies, impacts on power production or energy demand may not directly have large aggregate economic consequences, but they may have feedback effects on greenhouse gas mitigation efforts and, in turn, the economy, which would be captured in an economy-wide model. Such models can also capture adaptive responses that can mediate economic impacts (e.g., switching away from inputs and activities that are impacted by climate). Finally, there is significant uncertainty in all of these estimates. Our goal is to assess uncertainty in the aggregate responses more completely and to introduce other impacts. Such quantification of impacts can provide important information and understanding that can help guide decisions about actions, investments and policy.

More information

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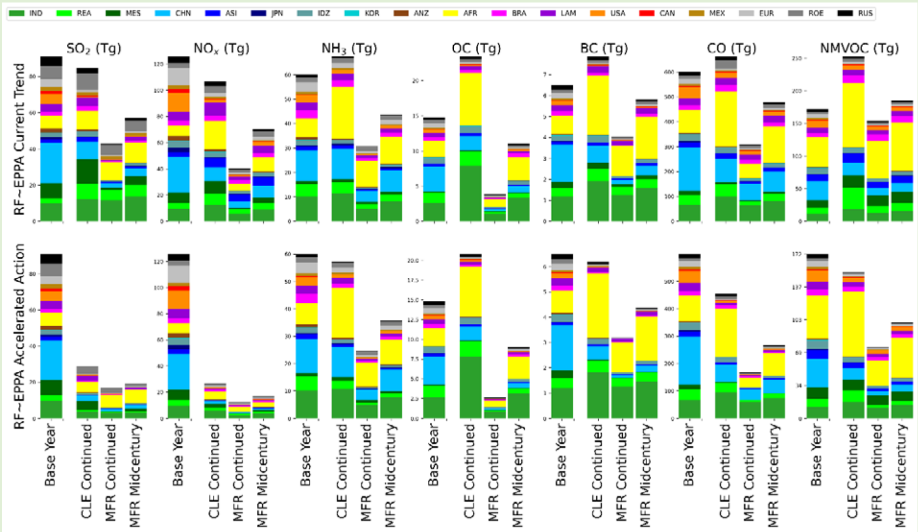

Figure 30. Breakdown of projected air-pollutant emissions in 2100. Each of the seven columns corresponds to a single pollutant, and the bar shading indicates the EPPA region breakdown. Top: projections for the *Current Trends* scenario. Bottom: projections for the *Accelerated Actions* scenario. OC: organic carbon. BC: black carbon (soot). NMVOC: non-methane volatile organic compounds.

Climate, Air Quality and Health

Context

In addition to having direct yet different climate implications, the two scenarios considered within this Outlook—*Current Trends* and *Accelerated Actions*—also imply differences in global air quality and public health. We apply the Tool for Air Pollution Scenarios (TAPS) (Atkinson *et al.*, 2022) to explore what the implications of accelerated action might be for air pollution, and to understand how the air quality benefits of accelerated action could be magnified (or minimized) by non-climate regulations. TAPS generates region- and sector-specific estimates of air-pollutant emissions using output from the EPPA model, and explicitly accounts for the effect of air-quality legislation which might be implemented independent of climate regulation.

Key Findings

We consider three different air pollutant scenarios. The first, a continuation of current legislation (CLE Continued), assumes no strengthening in air pollution regulations beyond those already in place. The second, Maximum Feasible Reduction (MFR) Continued, assumes that all possible actions will be taken to reduce air pollution. Finally, MFR Midcentury corresponds to an intermediate scenario in which regulations are increased only until 2050. The results for pollutant emissions in 2100 are shown in **Figure 30** alongside the Base Year (2014) emissions for reference. Two of the most commonly considered air-quality pollutants, sulfur dioxide (SO_2) and nitrogen oxides (NOx), are expected to be significantly reduced as a consequence of climate regulation. These are two of the U.S. Environmental Protection Agency's regulated criteria pollutants and contribute to the formation of harmful fine particulate matter ($PM_{2.5}$) and ozone. For both SO_2 and NOx, transitioning from *Current Trends* to *Accelerated Actions* results in reductions of over 60% in year-2100 emissions, regardless of the air-pollutant scenario chosen. This reduction is due to the elimination of carbon-intensive sources such as coal power plants which also are responsible for large quantities of air pollution. Nonetheless, a further reduction of 41-62% is possible under MFR Continued compared to CLE Continued. Both climate- and air-quality-focused policies are therefore effective in mitigating public health impacts from air pollution, with the greatest benefits realized when both are applied together.

We find a different outcome for other key air pollutants. Ammonia, a key precursor for $PM_{2.5}$, is reduced by only 15-20% as a consequence of *Accelerated Actions*. This is important because recent research has suggested that regulation of ammonia may be one of the most effective mechanisms for mitigation of air pollution (Xu *et al.*, 2022). Emissions of black and organic carbon (BC and OC), both elements in $PM_{2.5}$, are also reduced by less than 32% due to the implementation of *Accelerated Actions* alone. This reflects not only the relatively minor role that these emissions play in determining climate policy, but also the fact that these emissions are mostly driven by activities unlikely to be significantly reduced by climate-focused regulation.

In each case however, implementation of air-quality-focused actions (MFR) results in reductions of over 46%. We find similar outcomes for carbon monoxide (CO) and non-methane volatile organic compounds (NMVOCs). Both of these chemicals are precursors for ozone formation, which is both a pollutant and greenhouse gas when present at low altitudes. This year-2100 snapshot does not take into account the cumulative benefit of rapid action on air quality, although in all cases, over 50% of the emissions reduction associated with the MFR Continued scenario is achieved under the MFR Midcentury scenario. This also does not account for how climate change and pollutant emissions can interact to mitigate or exacerbate public health outcomes (Eastham *et al.*, 2023).

Implications

Our findings show there are substantial co-benefits to climate mitigation actions that reduce emissions of important trace gases affecting air quality—and subsequently human health. However, we cannot rely purely on these co-benefits to solve air-quality problems. Future scenarios and policy mechanisms must be designed with more comprehensive targets that not only steer the planet to a safer climate, but also supports a cleaner environment and improved human health. These "climate-health" targets are active and ongoing areas of research within the MIT Joint Program.

More Information

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Managed Resources

Water: Emerging and Compounding Risks of Water Stress across the World's Major River Basins

Context

The Earth's weather and climate systems support the continual replenishment of fresh water to our rivers, lakes and aquifers, but we routinely rely on managed water systems to meet human demands. In coming decades, climate change, population growth and increased socio-economic activity will all directly impact water supplies and human water demands. Influenced by these factors, water shortages can adversely affect human health, geopolitical stability and environmental sustainability. To inform and prepare for these challenges, we assess emerging risks to global water resources by applying our Water Resource Systems (WRS) modeling platform to results produced by our Outlook scenarios. The WRS tracks the ability of water supplies to meet the demands placed by the agriculture, energy, industrial and municipal sectors within the Earth's major river basins.

Key Findings

We consider two important metrics of "stress" (or shortage) in water resources: 1) an "environmental" index that indicates when the use of water (measured as total withdrawal from a body of water) has exceeded one-third of its natural replenishment (river flow and groundwater recharge); and 2) a "societal" index that indicates when 15% (or higher) of the basin's annual water demands cannot be met, even with optimal allocation of its water supply. For each of our Outlook scenarios, we track these two metrics at every WRS basin (282 globally) and assess the total population affected by either of these water stress measures as well as when they are concurrent to represent a compounding water-stressed situation.

We find (**Figure 31**) that by mid-century, in our *Current Trends* scenario, nearly 5.8 billion people will be exposed to shortfalls in water supply (societal stress) across the major river basins where they reside. In addition, 3.8 billion people will be living within basins exposed to environmental water stress. We also find that nearly 3.3 billion people will be exposed to both societal and environmental water-stressed conditions. With a global population projected to reach 9.9 billion by 2050, the *Current Trends* scenario indicates that more than half of the world's population (58%) will experience pressures to its water supply, and that at least 3 of every 10 people will live in water basins where the compounding societal and environmental pressures on water resources will be experienced. In the latter half of the century, the total population exposed to water-stress conditions will not only continue to increase (Figs. 28 and 29) but also accelerate relative to global population. By 2065, 6.5 billion people will be exposed to societal water stress out of a global population of 10.6 billion, resulting in 62% of the world's population (compared to 58% at mid-century).

To what extent could aggressive climate action alleviate these conditions, and on what scale must we consider adaptive measures? Population trends under combined water stress across the Outlook scenarios (**Figure 32**) reveal that the *Accelerated Actions* scenario could reduce approximately 40 million of the additional 570 million people living in water-stressed basins in the *Current Trends* scenario. We further find that over half of the combined water-stress trend is the direct result of population increases (360 million) across major river basins that are water-stressed under present-day climate conditions.

Implications

We find a modest "co-benefit" to accelerated climate action that reduces the global extent of water stress by mid-century. However, our findings highlight that much of the expected increases in population under heightened water stress by mid-century cannot be avoided or reduced by climate mitigation efforts alone, and can be remedied only through widespread transformations of water systems' capacities, conveyances and efficiencies. Any concerted efforts toward water sustainability must be prioritized to confront basins that face unprecedented and/or urgent threats in the coming decades. To that end, we have constructed a global map (**Figure 33**) that depicts an overall "threat score" of future water risk across the world's major river basins represented by the WRS projections. High-priority basins or regions include: Brahmaputra, Chad, Chile, Danube, East Africa, Huang He, India, Ganges, Mediterranean (Africa), Mongolia, Niger, Nile, North Africa, Rio Grande, South Africa, Tigris, Volta, West Africa and the Zambezi.

More Information

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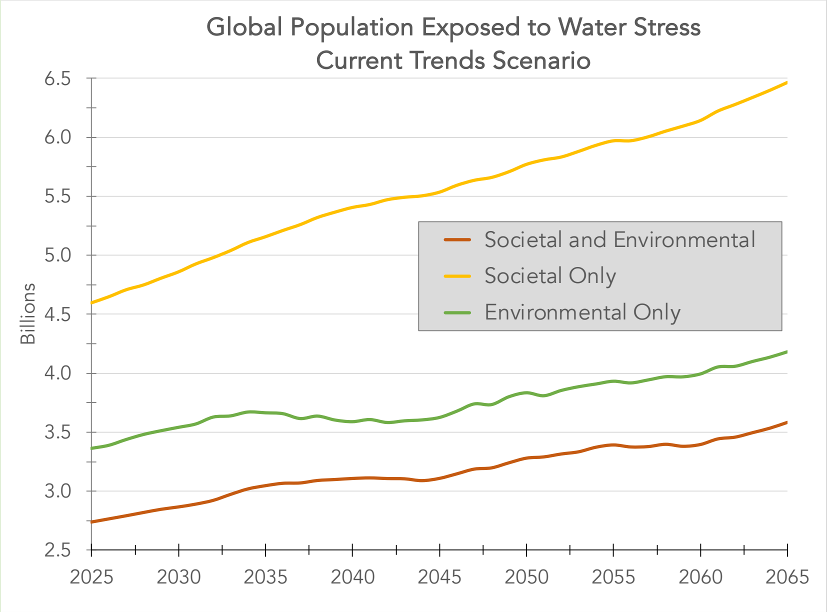

Figure 31. Projections from the *Current Trends* scenario indicate the global population exposed to individual and compounding societal and environmental threats of water stress.

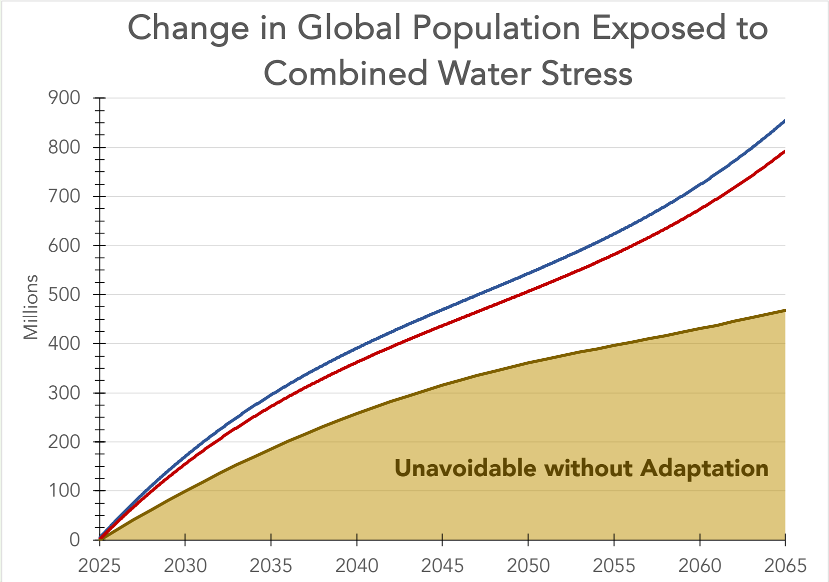

Figure 32. Projections of the change in global population that will be exposed to compounding societal and environmental threats of water stress. Results shown for the *Current Trends* (blue line) and *Accelerated Actions* (red line) scenarios. To highlight the long-term trends, a third-order polynomial fit is applied to the timeseries results of both scenarios.

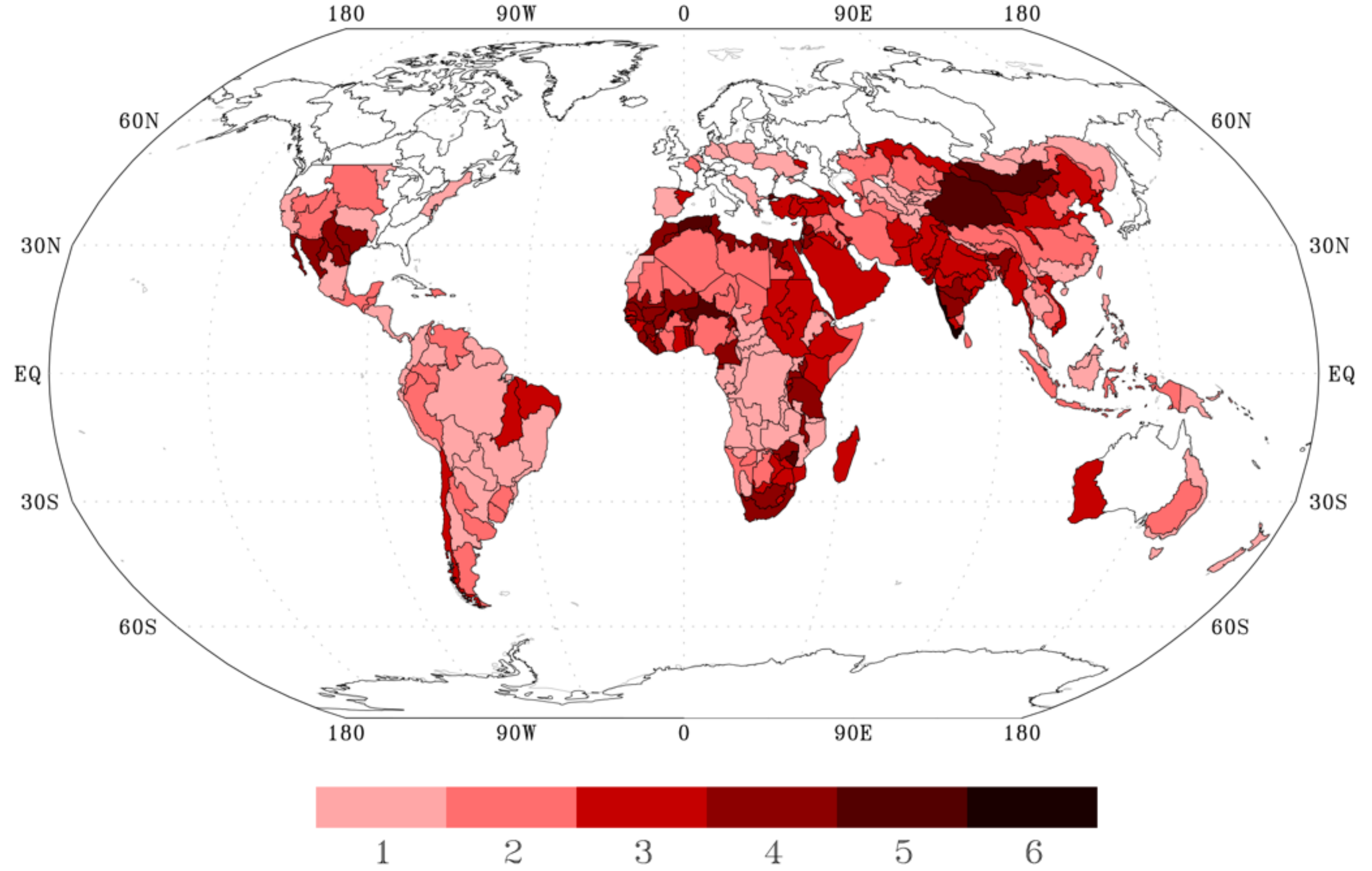

Figure 33. Global map of an aggregate future water-stress threat indicator of whether three conditions are met in both societal and environmental water stress indices: 1) a positive trend through the 2021-2059 period; 2) water-stress conditions occur for more than half of the period between 2021-2059; and 3) the index does not indicate widespread stressed conditions across 2020-2029 but they emerge by mid-century. A value of 6 indicates all three conditions are met for both water-stress indices (highest threat). Areas not shaded indicate none of the conditions are met for societal or environmental stress indices.

Agriculture

Context

The agriculture sector provides food, fiber, energy and other essentials for societies, but depends on intensive use of key managed natural resources such as land and water. Agricultural activities also contribute to substantial emissions of GHGs that contribute to climate change. Climate impacts may include reduced crop yields due to adverse growing conditions, and unexpected crop losses due to extreme events. Managing such risks requires understanding both trends in food demand (influenced by population and income growth, urbanization and shifts in diets), and supply (influenced by technological progress and weather patterns). Climate mitigation and adaptation policies are also important levers in addressing future sustainable agricultural production.

Key Findings

From 2020 to 2050, the value of agricultural output grows by 70% from crops and 61% from livestock, due to a 76% increase in food demand under the *Current Trends* scenario (**Figure 34**). As the value of food is composed of substantial shares of value-added (payments to capital and labor) and non-agricultural inputs (such as chemicals and energy), food production grows faster than livestock and crop production. Population trends are a key driver behind such increases, although economic growth and higher income are more relevant in determining the expansion of agricultural and food demand. While world population increases by only 24%, global GDP is 108% higher by 2050, implying a 67% increase in GDP per capita. As per-capita income grows, diets shift toward processed foods, leading to higher increases in food production.

Different world regions experience diverse trends in agriculture and food production, due to important emerging structural changes (**Figure 34**). Population and income grow slowly in Developed countries, implying lower increases in food and agricultural production than in other regions. In the Rest of the World, however, agricultural goods remain a significant share of final demand, and population and income growth accelerate, leading to more robust increases in food and agricultural output. India & China food consumption grows faster than in other regions until 2030, but it slows down compared to the Rest of the World toward mid-century. Livestock production, however, increases faster in India & China than in other regions, since income growth leads to shifts in diets toward more animal-protein-based sources.

Yield improvements enable the global population to avoid strong increases in agricultural and food prices from 2020 to 2050 (**Figure 35**). Food becomes just 1% more expensive, while crop prices increase more (10%). Food prices remain relatively stable, since the value-added component in food

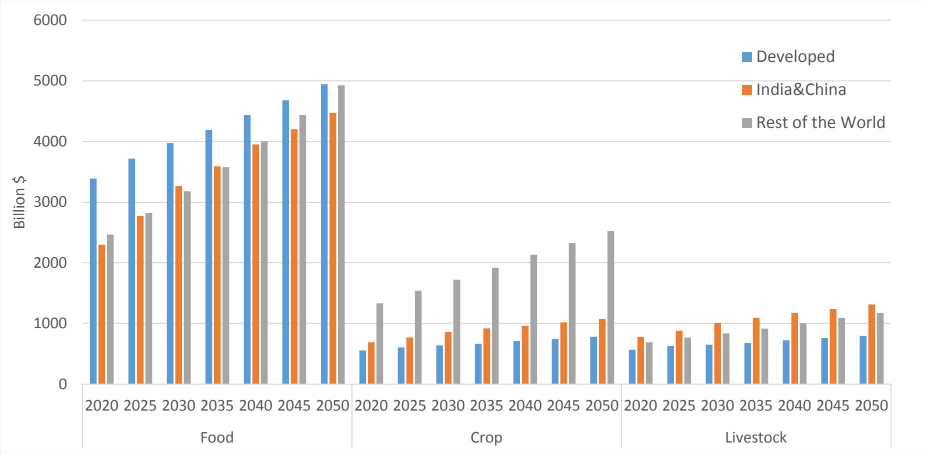

Figure 34. Food, crop and livestock production in Developed, India & China, and Rest of the World regions

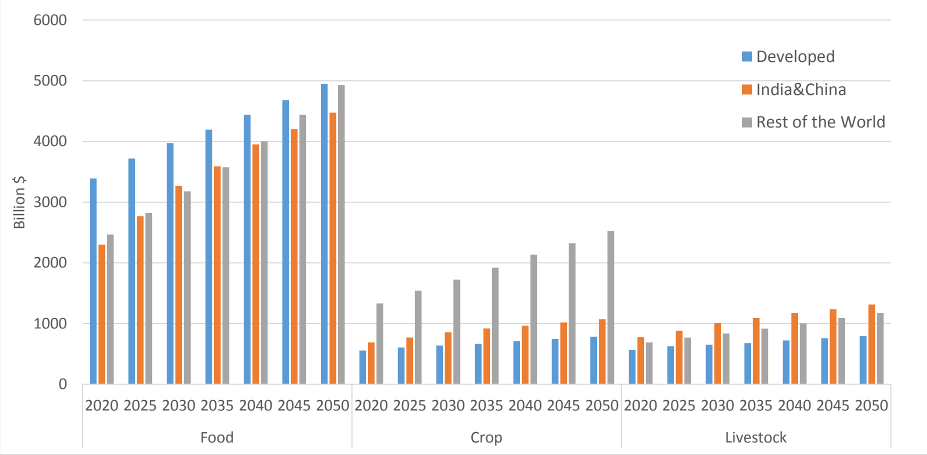

Figure 35. Global price indices for crop, livestock and food products

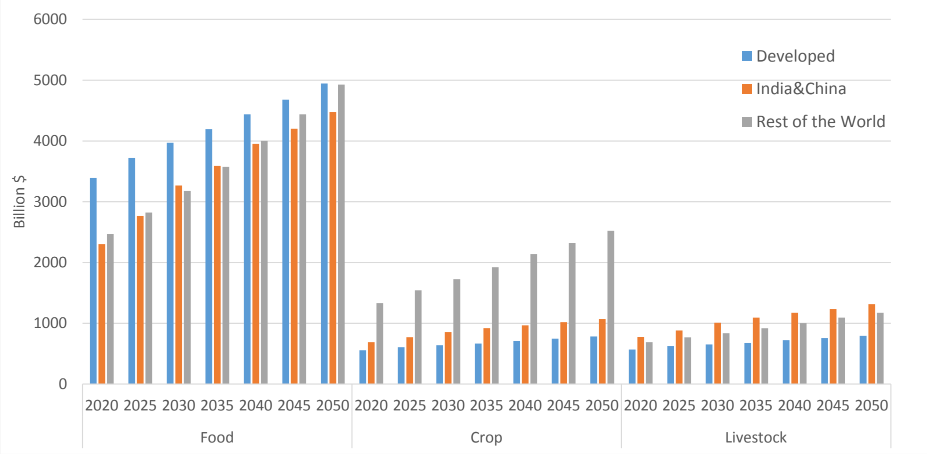

Figure 36. Changes in output and prices of crop, livestock and food in the *Accelerated Actions* scenario compared to the *Current Trends* scenario

production increases. Livestock prices rise by 26%. Higher demand for meat, driven by growth in per-capita income, pushes livestock prices up. Relatively large land input shares in the production costs of livestock are also relevant drivers influencing livestock prices.

Global projections for food and agriculture production and prices until 2050 under the *Accelerated Actions* scenario differ from those under the *Current Trends* scenario, mainly for the livestock sector (**Figure 36**). Food and crop outputs are 5% lower in the *Accelerated Actions* scenario respectively, while livestock output declines by 8.8%. Price changes for food and crops are quite similar to output changes, while prices of livestock products are highly impacted under *Accelerated Actions*, increasing by 26% in 2050 compared to the *Current Trends* scenario. Lower income and GDP growth under the *Accelerated Actions* scenario explain the overall decrease in output, while higher costs to comply with more stringent climate policies constrains the supply side more than the demand side, leading to higher prices. Changes in livestock prices reflect the fact that livestock are much more GHG emissions-intensive than crops and food, making livestock production more expensive.

Implications

Income and population growth in the Rest of the World and India & China regions by mid-century results in further increases in agriculture and food production. Consequently, GHG emissions from agriculture increase due to changes in land use and greater use of energy-intensive inputs to accommodate higher agriculture production. Higher incomes and populations also increase pressures on water resources. Under the *Accelerated Actions* scenario, less agricultural and food output is observed by 2050 compared to the *Current Trends* scenario, since this scenario affects economic growth and increases production costs. Livestock production is more GHG emissions-intensive than crop and food production, which, under carbon-pricing policies, drives demand downward and increases costs and prices. Such impacts are transmitted to the food sector and imply lower consumption of livestock-based products.

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Land-Use Change

Context

Land-use change is impacted by increasing agricultural and food demand. However, as natural areas are converted to agricultural use and become scarcer, investments in research and technology can help boost yields and thereby counterbalance agricultural land requirements. Declines in natural land areas also lead to growing pressures for conservation and protection of vegetation and habitats.

Key Findings

Global land-use projections from 2020 to 2050 under the *Current Trends* scenario are quite stable (**Figure 37**). Natural forest areas decrease by 1.4% and natural grasslands by 3%. These are converted mostly to cropland areas, which increase by 7.5%, while pasture lands decrease only by 1.8%. Crop-yield improvements explain the small changes in agricultural areas. A continuous intensification in the livestock sector leads to higher productivity and less need for pasture areas. Area dedicated to produce commercial biomass for bioenergy (liquid and bioelectricity)[1] increases by 45.8%, but as it occupies only 3% of total cropland in 2020, it covers only 4% of total cropland area by 2050.

Very different dynamics distinguish changes in agricultural land and natural areas around the world. Cropland areas in Developed countries are 1.7% smaller in 2050, while pasture areas decrease by 0.3% by 2050. Agricultural areas decrease due to a decline in population growth rates and improvements in yields. The natural grass area decreases by 0.8% by 2050, while natural forests increase by 0.4% in 2050.

Cropland in India & China decreases by 1.7% in 2050, while land for bioenergy grows by 78%, covering 4.3% of the total cropland area. Livestock intensification prevents strong increases in pasture areas, which grow by only 0.1% in 2050. Natural grass areas decrease by 0.5% in 2050 to provide space for pastureland and bioenergy, while natural forest areas increase by 3.2%, as these countries try to fulfill their climate-change and biodiversity commitments.

The Rest of the World region faces larger land-use changes than other regions, due to stronger population and income growth. By 2050, cropland area increases by 14%, and pasture area decreases by 2.5%. Cropland areas expand mostly at the expense of natural ecosystems. Natural grasslands decrease by 4.4% by 2050 and natural forests decrease by 2.5%. Land for bioenergy production undergoes major increases, growing by 91.6% by 2050. However, land dedicated to bioenergy reaches only 1.3% of total cropland area by 2050, since the area dedicated to commercial bioenergy in 2020 is quite small.

Land-use changes in the *Accelerated Actions* scenario are slightly different from those in the *Current Trends* scenario by 2050, except for land dedicated to bioenergy production, which is 44% larger in the *Accelerated Actions* scenario (**Figures 37 and 38**). At the World level, cropland area increases by 1%, while pastureland decreases by 4.2% in the *Accelerated Actions* scenario in comparison with *Current Trends*. At the regional level, cropland contracts in the Developed and India & China regions, while it expands in the Rest of the World under the *Accelerated Actions* scenario. This scenario requires strong efforts to reduce emissions at the end of the century, which have the greatest impact on the livestock sector, since it is more GHG emissions-intensive than crop production. It forces the Rest of the World region to meet the increasing demand for food by shifting toward crop production and intensifying livestock production. Together with stronger efforts to protect natural vegetation, such as the pledges to end deforestation at COP26 in Glasgow, the decrease in pasture areas provides space for a slightly larger area of natural forest (0.02%) and natural grassland (1%) than in the *Current Trends* scenario.

Implications

Productivity and yield gains prevent agricultural areas from expanding too much throughout the century. The *Accelerated Actions* scenario requires larger use of land for crops in the Rest of the World region and bioenergy everywhere, but forces some intensification in livestock production and sharp contraction in pasture areas. Efforts to protect natural areas prevent the loss of 14.5Mha in the *Accelerated Actions* compared to the *Current Trends* scenario, which represents 16% less deforestation relative to the 90Mha loss of natural vegetation in the *Current Trends* scenario. The strong expansion in biomass production in the *Accelerated Actions* scenario is not translated into larger deforestation rates, mostly due to productivity gains in livestock production under GHG emissions constraints, together with improvements in crop yields.

More Information

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[1] We do not track areas dedicated to traditional biomass and solid biomass production, which are embedded mostly in areas of managed and natural forests in our EPPA model.

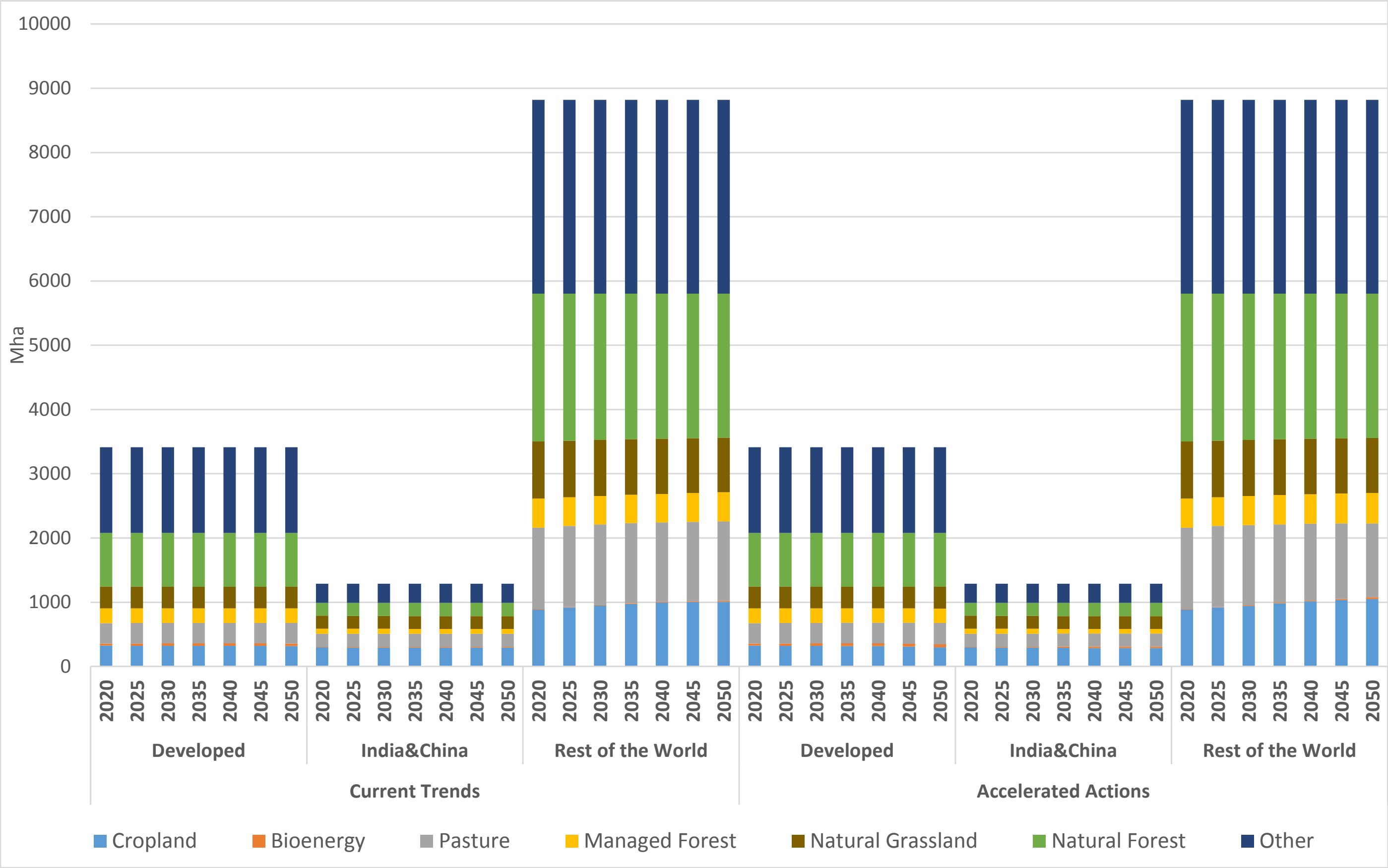

Figure 37. Land use in the Developed, India & China, and Rest of the World regions in the *Current Trends* and *Accelerated Actions* scenarios.

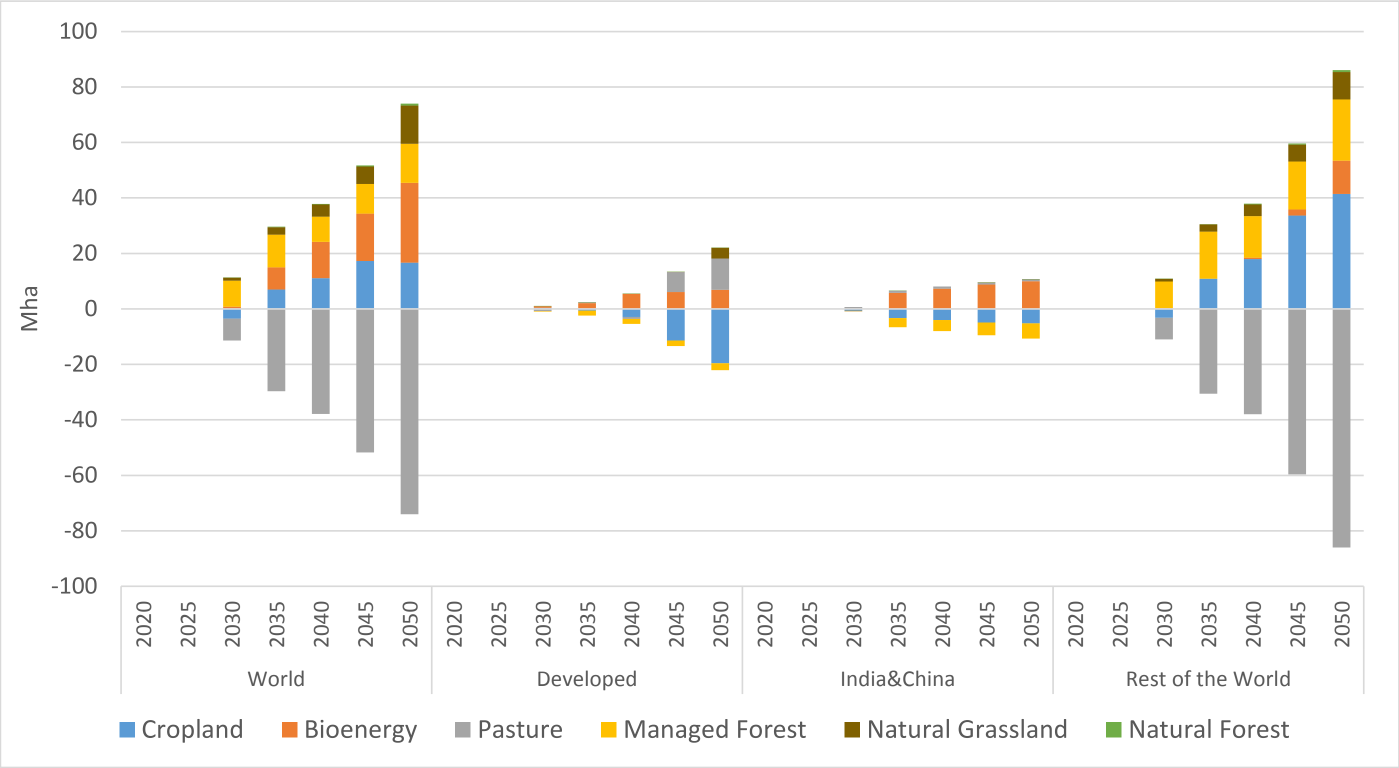

Figure 38. Differences in land use between the *Accelerated Actions* scenario and the *Current Trends* scenario in major regions and the World.

Policy Prospects

Prospects for Meeting Short-Term Paris Goals

The global climate regime will be stress-tested in the next few years as an inexorable gap grows between its long-term temperature goals and current prospects for cutting global greenhouse gas emissions. Perhaps this problem was to be expected. For the daunting challenge of managing the global commons, there is no means of enforcing action by sovereign states. While many of these states have made substantial progress, the pace will need to accelerate significantly to sustain confidence over the long term.

The heart of the regime, the 2015 Paris Agreement, is the product of a multi-decade effort to mobilize all nations to participate in ongoing, collective action to stabilize the global climate. Its key feature is a system of pledge and review, with a five-year ratchet of increasing ambition. At the outset, each nation declares its Nationally Determined Contribution (NDC) to the global reduction of GHG emissions, allowing international review of its performance.

Some notable progress to date

At present, 195 nations have posted NDCs for 2030. Also, though delayed by the pandemic, many have kept to the Paris Agreement schedule and announced upgrades near the five-year mark (2020). All face new decisions in 2025.

In addition to concern about the climate threat itself, a nation risks "blame and shame" if it fails to submit a serious NDC, or to take appropriate measures to meet it. Bolstered by these motivations, the Paris regime has contributed to a substantial shift in the global economy, as evidenced in a comparison among recent MIT Global Change Outlooks. For example, this Outlook's projection of global GHG emissions in 2030, given declared NDCs, is 12% below the 2015 Outlook estimate (prepared before the Paris Agreement), even though the later projection assumes higher GDP growth over the reporting period.

A multitude of national and subnational policies, and individual and corporate commitments, contribute to this projected achievement. Two advances in key sectors provide a taste of the transition that's underway. First, solar and wind have become price-competitive with fossil electricity in many markets due to cost reductions. Aided by policy incentives, they constitute a rapidly growing share of global electricity supply. Second, the International Energy Agency projects the electric vehicle fleet to grow by an average of 30% annually to 2030, supported by auto manufacturers' commitment to electric vehicles and massive investments in battery-making and charging stations.

Driving these developments is the pressure to meet the Paris Agreement's long-term temperature goals. The notion of a 2°C global warming limit as a policy objective has a long history, often serving as a convenient target for climate modeling studies. In 2010 it was adopted by the UN Framework Convention on Climate Change as a goal of the global effort. Flood-threatened small-island states and environmental groups had long argued for a target tighter than 2°C, and this desire was finally realized in the Paris negotiations. The Agreement set its overarching goal to limit warning to "well less than" 2°C, and to "pursue efforts" to hold to 1.5°C. This remains the official Paris terminology, though in public discussion of climate policy, 1.5°C has been elevated to the central and crucial objective (e.g., in comments by the UN Secretary-General).

An urgent need to increase ambition

As useful as they have proven to be, the initial NDCs were clearly far from putting the globe on a path to either of these goals, particularly the tighter 1.5°C, and the increased ambition declared by several nations at the 2020 ratchet point was insufficient to make a perceptible change in trajectory. Now, under added pressure from the Global Stocktake set in the Paris Agreement for 2023, signatory nations will face a series of decisions in 2025. These will include not only a question of increased ambition for 2030 but also decisions about NDCs for 2035 and perhaps later periods.

Gaining pledges of increased ambition for 2030 will be difficult, not only due to the short time horizon but also because many nations are not on a path to meet even their existing NDCs. The 2022 Gap Report by the UN Environment Program finds that, with existing policies, most G20 nations will fail to meet their NDCs. For the global total, the study projects 2030 GHG emissions will be 5% to 10% higher than if all NDCs were met. The uncertain range depends on the willingness of richer countries to meet the aid requirement assumed in "contingent" NDCs submitted by many developing nations. Considering that pledges of financial aid, such as the mobilization of $100 billion per year beginning 2020, have not been met, the outcome is likely nearer the upper end of the range.

The United States is prominent among the nations unlikely to meet their NDCs for 2030. Its pledge includes an emissions reduction of 50% to 52% below the 2005 level. Even including the substantial funding for low-carbon energy provided in the Inflation Reduction Act, a review of available analyses finds that on its current trajectory the U.S. will achieve only a 33-40% reduction.

Widespread public recognition of these two gaps—between negotiated temperature goals and national pledges of emissions reduction, and between these pledges and actual performance—heightens the risk of a loss of faith in the Paris Agreement and of support for the obligations it imposes. A challenge in coming years will be to steer through this tension in the Paris structure, and to sustain what is likely the best agreement possible among sovereign states. While recognizing progress to date, this will require leadership in pushing for ever-greater efforts within the Agreement's provisions. A clear and urgent first step must be to spur action by nations that are not yet on a path to meet their existing pledges for 2030.

More Information

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Prospects for Meeting Long-Term Paris Goals

Context

Over the past few decades, reports of the Intergovernmental Panel on Climate Change (IPCC) have established scientific foundations for targets and timetables needed to avoid "dangerous" human-forced global temperature increases. At the 21st United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP21) meeting in Paris in 2015, targets were formally established that keep global average temperature "well below 2°C above preindustrial levels" with the ultimate aim of preventing the temperature increase from exceeding 1.5°C. The COP21 meeting also resulted in the first-ever formal commitments by many nations to begin limiting greenhouse gas (GHG) emissions to achieve these targets. However, the COP21 emissions-reduction commitments only extend to 2030, with the expectation that more aggressive and long-term commitments would be established. Since then, other international commitments have been established, such as the Methane Pledge and COP26 Deforestation Pledge, to combat human-forced climate change. Yet all these commitments are challenged by geopolitical conflicts and other globally disruptive events such as the COVID pandemic. Therefore, it remains unclear that any of these commitments can be fully achieved.

To reflect this situation, our *Current Trends* scenario assumes that commitments are not entirely fulfilled, and that beyond 2030 there are no substantial emissions reductions. On the other hand, our *Accelerated Actions* scenario follows an aggressive pathway to meet the target of not exceeding 1.5˚C global warming. Based on these scenarios, we can better understand the prospects for avoiding "dangerous" outcomes and the likelihood of achieving these goals can be made. Taking a probabilistic approach with our Integrated Global System Modeling (IGSM) framework allows us to assess a comprehensive distribution of socio-economic pathways, climate responses, and impacts.

Key Findings

By design, and throughout the 2020s and 2030s, the *Current Trends* and *Accelerated Action* scenarios are indistinguishable in terms of increased radiative forcing and global CO_2-equivalent concentrations (**Figure 39**). However, starting in the 2040s, these pathways exhibit more distinct trajectories. *Accelerated Actions* undergoes a nearly monotonic decline through the remainder of the 21st century, and then remains constant through the middle of the 22nd. In contrast, climate forcing and GHG concentrations in the *Current Trends* scenario continue to rise in the latter half of this century and through the mid-22nd century. Another important distinction between these two scenarios is that by 2100, radiative forcing in the *Accelerated Actions* must decline to levels that are approximately 10% below what the planet is currently experiencing.

In both scenarios, temperatures continue to rise through the next two decades (**Figure 40**), and differences between the scenarios are indistinguishable up through the 2030s. By the 2040s, the scenarios deviate and while the global temperature response levels off by mid-century in *Accelerated Actions*, climate forcing (and corresponding emissions) must continue

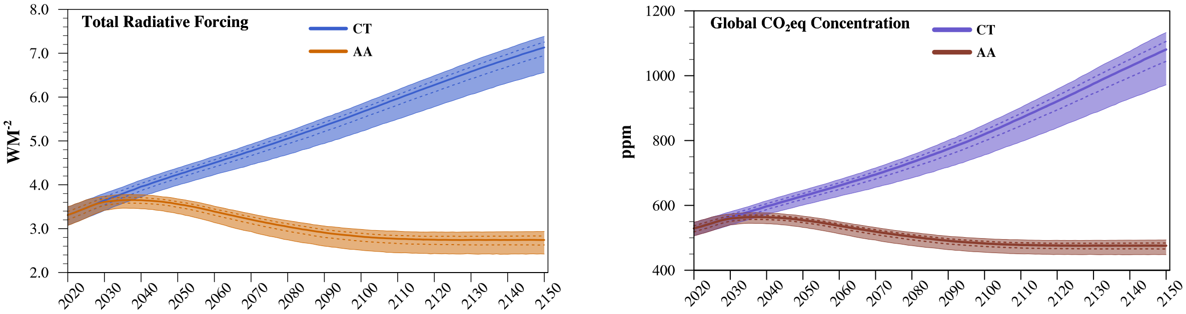

Figure 39. Total radiative forcing (W/m^2, left) and global CO_2 equivalent (CO_2e) concentration (ppm, right) that result from EPPA emissions of greenhouse gases, based on the *Accelerated Actions* and *Current Trends* (orange and blue shading/lines for radiative forcing and CO_2, respectively) ensemble scenarios. Values are calculated from a baseline forcing at 1861-1880. In each panel, the solid line represents the median result; the dashed lines denote the interquartile range (25th to 75th percentile range); and the shaded region depicts the 5th to 95th percentile range of values.

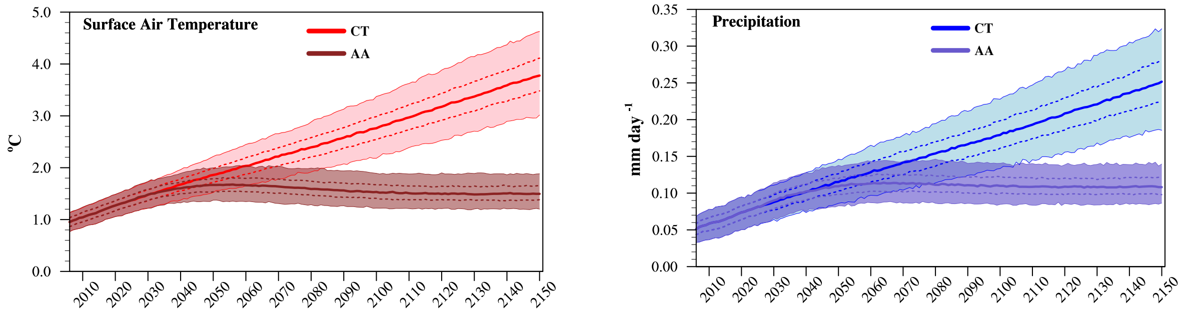

Figure 40. Annual, global temperature changes (˚C, leftl) and precipitation (mm/day, right) based on the MIT IGSM ensemble projections of the *Current Trends* (CT, lighter shading and lines) and *Accelerated Actions* (darker shading and lines) scenarios. Changes are calculated from the 1861-1880 mean. In each panel, the solid line represents the median result; the dashed lines denote the interquartile range; and the shaded region depicts the 5th to 95th percentile range of values. As a reference to the changes shown for global precipitation, 0.05 mm/day is approximately 9,300 km^3 or 2.5 quadrillion gallons of water annually, and commensurate to humans' global, annual impact on water resources.

to decline through the entire course of the 21st century. The ensemble results of this scenario indicate that the world can be virtually assured of remaining below 2˚C of global-averaged warming.

With any rise in global temperature, the global hydrologic sensitivity dictates that global precipitation (**Figure 40**) must also rise. Thus the current global precipitation rate is approximately 0.05 mm/day higher (or approximately a 2.5% increase) than preindustrial conditions as a result of the warming that has already occurred. As previously shown (**Figure 19**), under the *Current Trends* scenario, global precipitation is projected to continually rise such that by the middle of the next century, the range in global precipitation change will be between 0.18 to 0.32 mm/day, or 8-16% higher than pre-industrial rates. The *Accelerated Actions* scenario not only ceases the precipitation increase by mid-century, but substantially reduces the magnitude of change (about half that projected by the *Current Trends* scenario) as well as the total range of plausible increases.

Additional physical risks associated with human-induced warming include global sea-level rise (GSLR) and ocean salinity. The physical mechanisms of GSLR associated with human-induced warming are understood, yet substantial uncertainties and limitations in model projections exist. These are related to global climate sensitivity, regional hydro-climatic and cryosphere changes, as well as ice-sheet ablation and dynamics. Nevertheless, our Outlook projections indicate that the probability of end-of-century GSLR exceeding 1 meter under *Current Trends* is at least 80%, but this can be reduced to 5-20% in *Accelerated Actions*. That said, as noted above, through mid-century our scenarios show very little differences in the climate responses, and thus both scenarios indicate GSLR to most likely be 0.25 meters. Projected risks to ocean acidification indicate similar end-of-century benefits from *Accelerated Actions*. We expect ocean acidity by 2100 to increase by most likely 60% under *Current Trends*, and as low as 10% under *Accelerated Actions*.

Implications

While our *Current Trends* scenario represents the substantial global commitments now in place to limit greenhouse gas emissions, it neither stabilizes climate warming nor reduces the pace of human-forced climate change through the century. The IGSM Outlook scenarios indicate there are unavoidable, heightened risks in this regard, but aggressive mitigation represented in the *Accelerated Actions* scenario substantially reduces the likelihood of the more severe outcomes. Nevertheless, the ability for nations to uphold their commitments that are implied in either of the Outlook scenarios will be challenged by geopolitical conflicts as well as unforeseen and uncertain global-scale disruptions.

More Information

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Preparing for Tomorrow Today

The world is getting warmer, the atmosphere more humid, and climate extremes more intense and frequent. Arctic summer sea ice is receding more quickly; the Greenland and Antarctic ice sheets are retreating faster; tropical cyclones are intensifying, creating larger storm surges and more intense precipitation with severe flooding; droughts and extreme heat events are intensifying and fueling more widespread wildfires. These trends, on scales from local to global, are now impacting—and in coming decades likely to further impact—vulnerable infrastructure, supply chains, ecosystems and human health.

Our projected global climate responses under the *Current Trends* scenario indicate with near-certainty that the world will surpass important greenhouse gas concentration thresholds and climate targets in the coming decades. Many regions of the world are likely to experience more pronounced, unprecedented extreme-temperature events as human-forced climate warming intensifies.

Our projections underscore that despite growing geopolitical tensions, the world must take bolder, more collaborative actions to mitigate and adapt to climate change as soon as possible. In our *Accelerated Actions* scenario, we show how robust global efforts to mitigate greenhouse gas emissions can lead to achieving the world's aggressive, long-term goal of keeping the rise in global average surface temperature (above preindustrial levels) well below two degrees Celsius. Such actions will dramatically reduce the physical risks posed by climate change. At the same time, the world needs to increase investments in adaptation because even limited climate change—particularly that which is unavoidable—elevates the risks of extreme events. The focus of adaptation activities should be on those most impacted by climate change: people experiencing poverty, indigenous groups, people of color and other vulnerable groups.

We find that more aggressive efforts to reduce emissions globally can virtually assure the world of remaining below 2°C of global warming. Nevertheless, additional policy mechanisms must be designed with more comprehensive targets that also support a cleaner environment, sustainable resources, as well as improved and equitable human health. To make the world better tomorrow, large-scale, dramatic and sustained greenhouse gas emissions-reduction efforts across the globe need to start today.

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Appendix

This appendix contains projections for global economic growth, energy use, emissions and other variables to 2050 under different Outlook scenarios and regions as specified. Similar tables for 18 regions of the world in all Outlook scenarios are available at http://globalchange.mit.edu/Outlook2023.

MIT Global Change Outlook 2023

Projection Data Tables

Region: World **Scenario: Current Trends**

		Units	2020	2025	2030	2035	2040	2045	2050
Economic Indicators	GDP	bil 2021 $	97210.5	114244.4	129681.1	145170.2	162643.0	181884.4	201855.2
	Consumption	bil 2021 $	53719.0	63851.1	72579.6	81134.1	90810.1	100900.0	111692.7
	GDP growth	% / yr	1.2	3.3	2.6	2.3	2.3	2.3	2.1
	Population	millions	7803.1	8153.8	8509.9	8845.3	9156.8	9439.5	9685.5
	GDP *per capita*	2021 $	12457.9	14011.3	15238.9	16412.1	17761.9	19268.5	20840.9
GHG Emissions	CO_2 – fossil	Mt CO_2	30876.9	32478.0	33151.7	32154.9	31310.5	30531.9	29388.0
	CO_2 – industrial	Mt CO_2	1558.4	1652.2	1691.7	1764.7	1833.3	1758.5	1763.2
	CH_4	Mt	356.4	339.8	326.8	324.8	325.4	326.0	327.8
	N_2O	Mt	10.1	10.2	10.1	10.1	10.3	10.6	10.8
	PFCs	kt CF_4	19.1	7.7	6.0	5.9	6.0	5.8	6.0
	SF_6	kt	5.8	5.3	5.0	4.7	4.5	4.2	4.0
	HFCs	kt HFC-134a	420.6	356.2	366.9	381.1	411.2	437.1	470.0
	Total GHG net of Land Use	Mt CO_2e	46073.7	47113.0	47439.2	46488.5	45826.7	45090.5	44115.3
	CO_2 – land use change	*Mt CO_2*	*1286.5*	*828.3*	*682.6*	*566.8*	*471.3*	*405.1*	*366.6*
Primary Energy Use	Wind	EJ	5.1	10.5	15.7	21.6	27.1	33.2	40.2
	Solar	EJ	2.9	6.8	11.1	15.6	20.5	24.1	29.6
	Bioenergy & other renewables	EJ	47.6	49.0	50.2	51.1	51.8	50.6	50.1
	Hydro	EJ	15.6	16.6	17.9	19.2	20.5	21.7	22.9
	Nuclear	EJ	26.6	29.0	31.8	33.2	35.6	37.9	40.0
	Coal	EJ	146.1	148.0	149.0	137.1	129.2	118.6	108.1
	Liquids	EJ	180.2	192.0	195.5	196.2	192.7	195.6	193.1
	Gas	EJ	139.4	153.2	163.6	165.8	168.3	167.7	168.0
	Total Primary Energy Use	EJ	563.5	605.0	634.8	639.8	645.8	649.5	652.0
Electricity Production	Wind	TWh	1429.6	2929.0	4391.9	6058.7	7605.1	9320.1	11280.9
	Solar	TWh	799.6	1878.3	3077.1	4327.6	5697.2	6706.9	8211.8
	Bioenergy & other renewables	TWh	715.4	880.3	1018.7	1143.2	1227.5	1297.4	1383.5
	Hydro	TWh	4334.5	4619.7	4962.0	5335.4	5698.4	6021.8	6350.8
	Nuclear	TWh	2808.8	3061.3	3355.4	3500.4	3759.3	3997.3	4225.6
	Coal-no CCS	TWh	9301.7	8823.1	8342.7	7187.2	6430.9	5666.2	5012.5
	Coal-CCS	TWh	0.0	0.0	0.0	0.0	0.0	0.0	7.3
	Petroleum	TWh	860.1	800.0	634.7	518.7	409.2	346.7	295.5
	Gas-no CCS	TWh	6279.3	7227.5	8217.8	8529.1	8766.6	9317.1	9523.8
	Gas-CCS	TWh	0.0	1.8	4.1	22.0	21.0	33.0	51.4
	Total Electricity Production	TWh	26529.0	30221.1	34004.4	36622.2	39615.2	42706.6	46343.1

Region: World **Scenario: Current Trends**

		Units	2020	2025	2030	2035	2040	2045	2050
Land Use	Cropland	Mha	1507.3	1535.5	1563.3	1586.0	1608.5	1614.2	1620.5
	Bioenergy & Renewables	Mha	45.1	52.9	58.4	62.3	63.9	64.3	65.8
	Pasture	Mha	1792.2	1785.5	1775.5	1769.8	1759.2	1761.0	1759.2
	Managed forest	Mha	764.3	753.0	746.9	741.8	742.7	747.7	753.4
	Natural grassland	Mha	1427.5	1419.7	1411.7	1404.0	1396.8	1390.4	1384.5
	Natural forest	Mha	3333.8	3323.6	3314.3	3306.2	3299.0	3292.5	3286.8
	Other	Mha	4650.9	4650.9	4650.9	4650.9	4650.9	4650.9	4650.9
Air Pollutant Emissions	SO$_2$	Tg	82.0	75.8	68.4	59.3	52.4	46.9	41.9
	NO$_x$	Tg	112.7	119.3	122.9	124.5	125.6	127.6	129.3
	Ammonia	Tg	48.7	54.3	58.6	62.0	65.5	67.8	70.2
	Volatile organic compounds	Tg	143.0	157.7	169.4	178.8	188.9	196.4	204.3
	Black carbon	Tg	4.4	4.4	4.2	4.0	3.8	3.6	3.3
	Organic particulates	Tg	10.3	10.5	10.4	10.1	9.8	9.3	8.8
	Carbon monoxide	Tg	572.4	638.7	692.6	735.8	783.4	817.2	849.1
Agricultural & food outputs	Crop	bil 2021 $	2925.6	3311.8	3657.0	3983.1	4327.9	4644.8	4973.2
	Livestock	bil 2021 $	2308.5	2584.9	2839.0	3056.9	3291.5	3504.8	3726.5
	Forest	bil 2021 $	438.9	539.7	635.6	724.8	828.1	923.6	1028.3
	Food	bil 2021 $	9260.3	10573.0	11828.9	12899.5	14070.8	15127.9	16295.4
Agricultural & food prices (2021 price = 1)	Crop			1.1	1.1	1.1	1.1	1.1	1.1
	Livestock			1.1	1.1	1.2	1.2	1.2	1.2
	Forest			1.1	1.1	1.1	1.2	1.2	1.2
	Food			1.0	1.0	1.0	1.0	1.0	1.0
Energy prices (2021 price = 1)	Coal			1.0	1.0	1.0	0.9	0.9	0.9
	Oil			1.1	1.1	1.1	1.1	1.1	1.1
	Gas			1.0	1.0	1.0	1.0	1.2	1.3
	Electricity			1.0	1.0	1.0	1.0	1.1	1.1

Region: World Scenario: Accelerated Actions

		Units	2020	2025	2030	2035	2040	2045	2050
Economic Indicators	GDP	bil 2021 $	97210.5	114244.4	128071.0	142458.6	157921.8	173277.0	188254.9
	Consumption	bil 2021 $	53719.0	63851.1	71807.8	79773.5	88452.3	96785.9	104853.4
	GDP growth	% / yr	1.2	3.3	2.3	2.2	2.1	1.9	1.7
	Population	millions	7803.1	8153.8	8509.9	8845.3	9156.8	9439.5	9685.5
	GDP *per capita*	2021 $	12457.9	14011.3	15049.7	16105.5	17246.3	18356.7	19436.7
GHG Emissions	CO_2 – fossil	Mt CO_2	30876.9	32478.0	24465.5	19606.6	15726.2	12174.6	8463.6
	CO_2 – industrial	Mt CO_2	1558.4	1652.2	1137.2	1064.7	908.0	869.2	739.1
	CH_4	Mt	356.4	339.8	282.3	260.8	246.4	228.4	209.7
	N_2O	Mt	10.1	10.2	9.3	9.0	8.7	7.9	6.9
	PFCs	kt CF_4	19.1	7.7	5.3	5.3	5.0	4.4	3.7
	SF_6	kt	5.8	5.3	4.2	3.3	3.2	3.1	3.0
	HFCs	kt HFC-134a	420.6	356.2	322.0	334.4	340.2	355.1	356.0
	Total GHG net of Land Use	Mt CO_2e	46073.7	47113.0	36652.2	31029.7	26516.4	22237.0	17587.1
	CO_2 – land use change	*Mt CO_2*	*1286.5*	*828.3*	*674.9*	*553.3*	*462.6*	*385.6*	*333.5*
Primary Energy Use	Wind	EJ	5.1	10.5	19.1	32.9	42.0	48.2	57.1
	Solar	EJ	2.9	6.8	10.5	16.1	23.8	32.9	47.6
	Bioenergy & other renewables	EJ	47.6	49.0	50.1	52.2	54.0	53.8	56.0
	Hydro	EJ	15.6	16.6	19.2	21.1	22.4	23.9	25.1
	Nuclear	EJ	26.6	29.0	32.5	51.1	49.8	56.4	63.0
	Coal	EJ	146.1	148.0	87.4	52.6	47.3	39.8	29.8
	Liquids	EJ	180.2	192.0	183.2	172.2	155.6	132.6	105.2
	Gas	EJ	139.4	153.2	125.6	108.5	84.7	62.5	37.5
	Total Primary Energy Use	EJ	563.5	605.0	527.7	506.7	479.6	450.1	421.4
Electricity Production	Wind	TWh	1429.6	2929.0	5338.7	9184.4	11779.8	13550.6	16111.5
	Solar	TWh	799.6	1878.3	2918.0	4484.2	6601.8	9128.7	13226.5
	Bioenergy & other renewables	TWh	715.4	880.3	1021.3	1268.8	1477.6	1653.2	1989.9
	Hydro	TWh	4334.5	4619.7	5333.1	5872.7	6216.0	6649.4	6969.2
	Nuclear	TWh	2808.8	3061.3	3433.4	5396.7	5261.9	5955.7	6655.1
	Coal-no CCS	TWh	9301.7	8823.1	4820.0	935.1	459.4	250.7	54.1
	Coal-CCS	TWh	0.0	0.0	131.9	697.9	2003.0	2168.4	1910.8
	Petroleum	TWh	860.1	800.0	284.9	109.5	38.0	11.9	0.0
	Gas-no CCS	TWh	6279.3	7227.5	7632.9	6258.6	4751.6	3596.4	2361.6
	Gas-CCS	TWh	0.0	1.8	33.7	67.8	83.0	120.6	178.9
	Total Electricity Production	TWh	26529.0	30221.1	30948.2	34275.4	38672.0	43085.6	49457.6

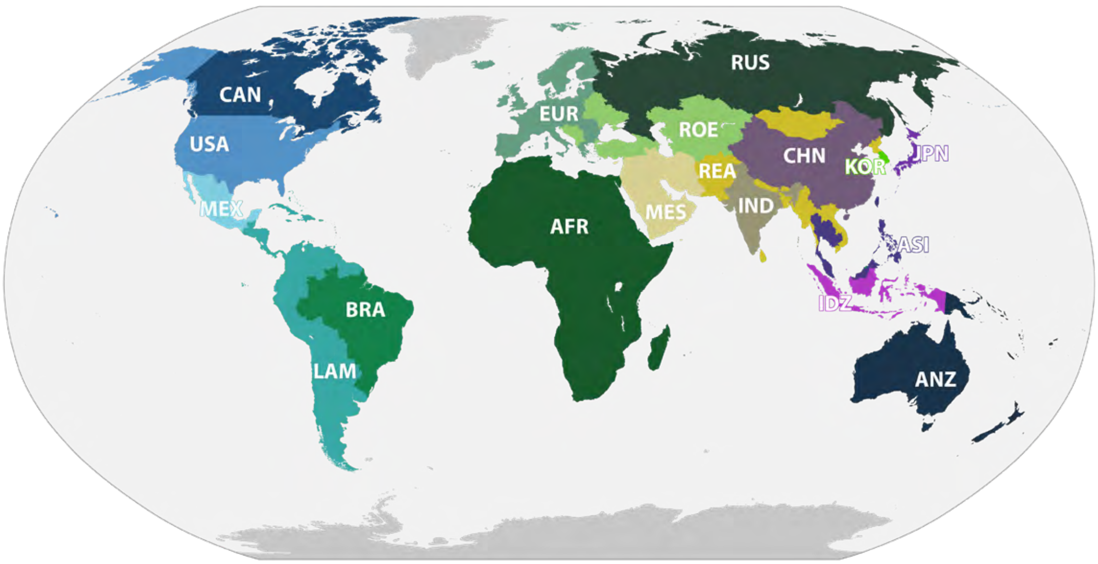
Region: World **Scenario: Accelerated Actions**

		Units	2020	2025	2030	2035	2040	2045	2050
Land Use	Cropland	Mha	1507.3	1535.5	1559.8	1593.1	1619.6	1631.5	1637.2
	Bioenergy & Renewables	Mha	45.1	52.9	59.2	70.2	77.0	81.4	94.6
	Pasture	Mha	1792.2	1785.5	1767.7	1740.1	1721.4	1709.2	1685.2
	Managed forest	Mha	764.3	753.0	756.3	753.7	751.8	758.5	767.4
	Natural grassland	Mha	1427.5	1419.7	1412.8	1406.7	1401.2	1396.7	1398.4
	Natural forest	Mha	3333.8	3323.6	3314.4	3306.4	3299.2	3292.9	3287.4
	Other	Mha	4650.9	4650.9	4650.9	4650.9	4650.9	4650.9	4650.9
Air Pollutant Emissions	SO_2	Tg	82.0	75.8	49.1	37.6	31.4	25.6	21.5
	NO_x	Tg	112.7	119.3	103.0	98.6	94.8	89.5	84.8
	Ammonia	Tg	48.7	54.3	56.3	57.7	59.6	60.0	59.6
	Volatile organic compounds	Tg	143.0	157.7	152.4	151.1	154.5	153.8	152.2
	Black carbon	Tg	4.4	4.4	3.7	3.3	3.0	2.6	2.3
	Organic particulates	Tg	10.3	10.5	9.7	8.9	8.4	7.6	6.9
	Carbon monoxide	Tg	572.4	638.7	633.2	636.4	655.3	655.6	651.6
Agricultural & food outputs	Crop	bil 2021 $	2925.6	3311.8	3627.0	3912.0	4216.8	4464.8	4706.8
	Livestock	bil 2021 $	2308.5	2584.9	2794.4	2971.0	3151.3	3282.3	3397.1
	Forest	bil 2021 $	438.9	539.7	626.5	707.1	796.5	872.3	949.3
	Food	bil 2021 $	9260.3	10573.0	11724.4	12698.8	13719.0	14587.3	15414.8
Agricultural & food prices (2021 price = 1)	Crop			1.1	1.1	1.1	1.1	1.1	1.1
	Livestock			1.1	1.1	1.2	1.3	1.4	1.6
	Forest			1.1	1.1	1.1	1.1	1.1	1.1
	Food			1.0	1.0	1.0	1.0	1.0	1.0
Energy prices (2021 price = 1)	Coal			1.0	0.8	0.7	0.7	0.7	0.8
	Oil			1.1	1.0	1.0	1.0	0.9	0.8
	Gas			1.0	1.1	1.0	1.0	1.0	0.9
	Electricity			1.0	1.2	1.2	1.2	1.3	1.4

EPPA regions:

AFR	Africa
ANZ	Australia & New Zealand
ASI	Dynamic Asia
BRA	Brazil
CAN	Canada
CHN	China
EUR	Europe (EU+)
IDZ	Indonesia
IND	India
JPN	Japan
KOR	South Korea
LAM	Other Latin America
MES	Middle East
MEX	Mexico
REA	Other East Asia
ROE	Other Eurasia
RUS	Russia
USA	United States

Regional data tables available at: http://globalchange.mit.edu/Outlook2023



Country	Region
Afghanistan	REA
Albania	ROE
Algeria	AFR
American Samoa	ANZ
Andorra	ROE
Angola	AFR
Anguilla	LAM
Antigua & Barbuda	LAM
Argentina	LAM
Armenia	ROE
Aruba	LAM
Australia	ANZ
Austria	EUR
Azerbaijan	ROE
Bahamas	LAM
Bahrain	MES
Bangladesh	REA
Barbados	LAM
Belarus	ROE
Belgium	EUR
Belize	LAM
Benin	AFR
Bermuda	LAM
Bhutan	REA
Bolivia	LAM
Bosnia and Herzegovina	ROE
Botswana	AFR
Brazil	BRA
Brunei	REA
Bulgaria	EUR
Burkina Faso	AFR
Burundi	AFR
Cambodia	REA
Cameroon	AFR
Canada	CAN
Cape Verde	AFR
Cayman Islands	LAM
Central African Republic	AFR
Chad	AFR
Chile	LAM
China	CHN
Côte d'Ivoire	AFR
Colombia	LAM
Comoros	AFR
Congo	AFR

Country	Region
Congo, Dem. Rep. (Zaire)	AFR
Cook Islands	ANZ
Costa Rica	LAM
Croatia	EUR
Cuba	LAM
Cyprus	EUR
Czech Republic	EUR
Denmark	EUR
Djibouti	AFR
Dominica	LAM
Dominican Republic	LAM
Ecuador	LAM
Egypt	AFR
El Salvador	LAM
Equatorial Guinea	AFR
Eritrea	AFR
Estonia	EUR
Ethiopia	AFR
Falkland Islands	LAM
Faroe Islands	ROE
Fiji	ANZ
Finland	EUR
France	EUR
French Guiana	LAM
French Polynesia	ANZ
Gabon	AFR
Gambia	AFR
Georgia	ROE
Germany	EUR
Ghana	AFR
Gibraltar	ROE
Greece	EUR
Greenland	LAM
Grenada	LAM
Guadeloupe	LAM
Guam	ANZ
Guatemala	LAM
Guinea	AFR
Guinea-Bissau	AFR
Guyana	LAM
Haiti	LAM
Honduras	LAM
Hong Kong	CHN
Hungary	EUR
Iceland	EUR

Country	Region
India	IND
Indonesia	IDZ
Iran	MES
Iraq	MES
Ireland	EUR
Israel	MES
Italy	EUR
Jamaica	LAM
Japan	JPN
Jordan	MES
Kazakhstan	ROE
Kenya	AFR
Kiribati	ANZ
Korea	KOR
Korea, Dem. Ppl. Rep.	REA
Kuwait	MES
Kyrgyzstan	ROE
Laos	REA
Latvia	EUR
Lebanon	MES
Lesotho	AFR
Liberia	AFR
Liechtenstein	EUR
Lithuania	EUR
Luxembourg	EUR
Libya	AFR
Macau	REA
Macedonia	ROE
Madagascar	AFR
Malawi	AFR
Malaysia	ASI
Maldives	REA
Mali	AFR
Malta	EUR
Marshall Islands	ANZ
Martinique	LAM
Mauritania	AFR
Mauritius	AFR
Mayotte	AFR
Mexico	MEX
Micronesia	ANZ
Moldova	ROE
Monaco	ROE
Mongolia	REA
Montserrat	LAM

Country	Region
Morocco	AFR
Mozambique	AFR
Myanmar	REA
Namibia	AFR
Nauru	ANZ
Nepal	REA
Netherlands	EUR
Netherlands Antilles	LAM
New Caledonia	ANZ
New Zealand	ANZ
Nicaragua	LAM
Niger	AFR
Nigeria	AFR
Niue	ANZ
Norfolk Islands	ANZ
Northern Mariana Islands	ANZ
Norway	EUR
Oman	MES
Pakistan	REA
Palestine	MES
Panama	LAM
Papua New Guinea	ANZ
Paraguay	LAM
Peru	LAM
Philippines	ASI
Poland	EUR
Portugal	EUR
Puerto Rico	LAM
Qatar	MES
Réunion	AFR
Romania	EUR
Russian Federation	RUS
Rwanda	AFR
Saint Helena	AFR
Saint Kitts and Nevis	LAM
Saint Lucia	LAM
Saint Pierre & Miquelon	LAM
Saint Vincent & Grenadines	LAM
Samoa	ANZ
San Marino	ROE
São Tomé and Príncipe	AFR
Saudi Arabia	MES
Senegal	AFR
Serbia and Montenegro	ROE
Seychelles	AFR

Country	Region
Sierra Leone	AFR
Singapore	ASI
Slovakia	EUR
Slovenia	EUR
Solomon Islands	ANZ
Somalia	AFR
South African Republic	AFR
Spain	EUR
Sri Lanka	REA
Sudan	AFR
Suriname	LAM
Swaziland	AFR
Sweden	EUR
Switzerland	EUR
Syria	MES
Taiwan	ASI
Tajikistan	ROE
Tanzania	AFR
Thailand	ASI
Timor-Leste	REA
Togo	AFR
Tokelau	ANZ
Tonga	ANZ
Trinidad and Tobago	LAM
Tunisia	AFR
Turkey	ROE
Turkmenistan	ROE
Turks and Caicos Islands	LAM
Tuvalu	ANZ
Uganda	AFR
Ukraine	ROE
United Arab Emirates	MES
United Kingdom	EUR
United States	USA
Uruguay	LAM
Uzbekistan	ROE
Vanuatu	ANZ
Venezuela	LAM
Vietnam	REA
Virgin Islands, British	LAM
Virgin Islands, U.S.	LAM
Wallis and Futuna	ANZ
Yemen	MES
Zambia	AFR
Zimbabwe	AFR

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