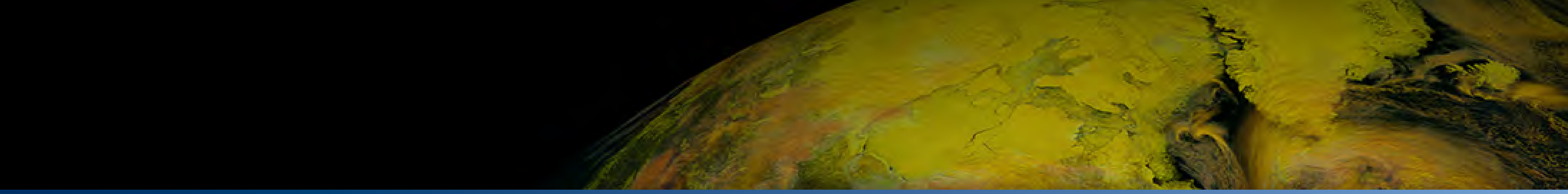

MIT JOINT PROGRAM ON THE SCIENCE AND POLICY OF GLOBAL CHANGE

2021 GLOBAL CHANGE OUTLOOK

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

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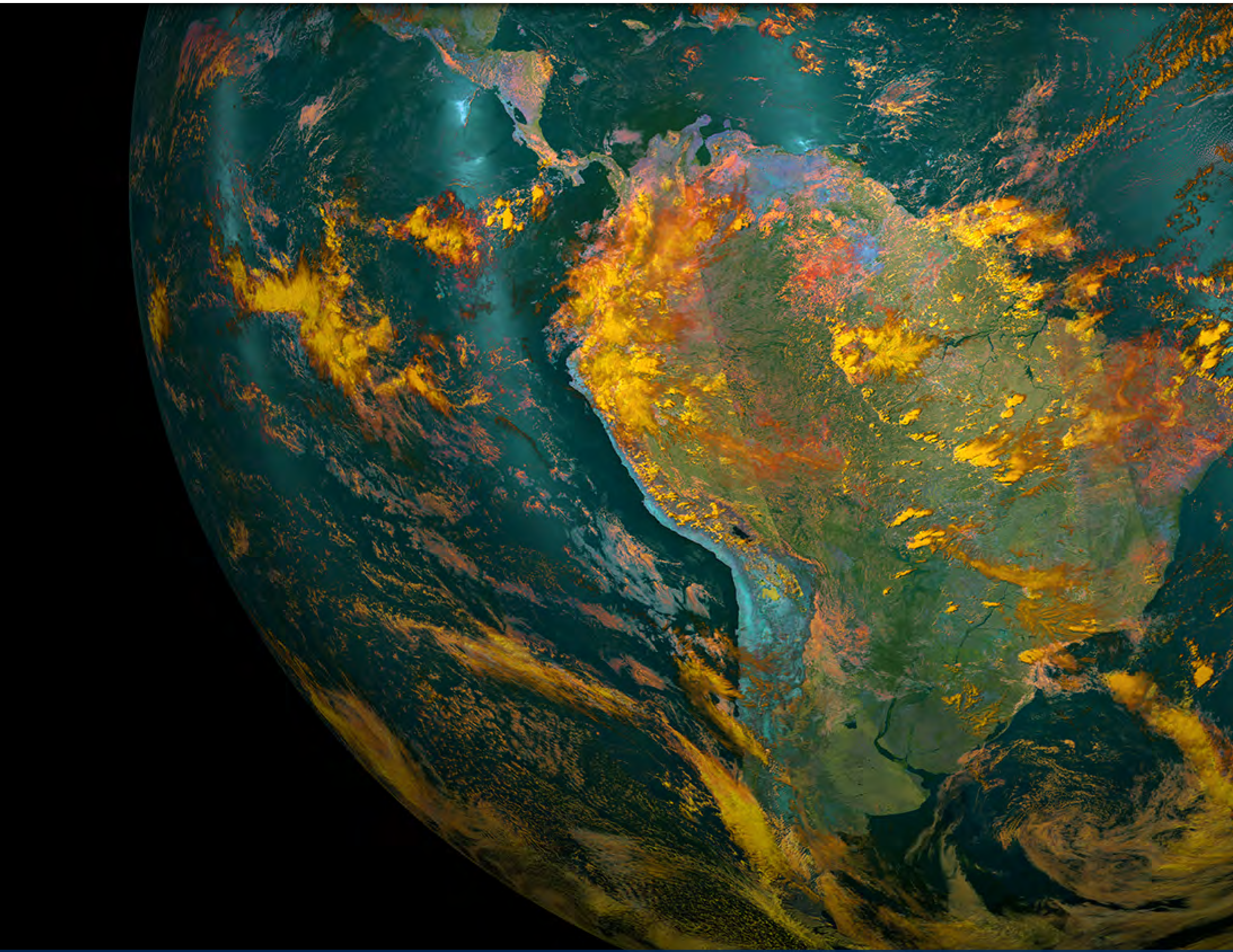

THE MIT JOINT PROGRAM ON THE SCIENCE & POLICY OF GLOBAL CHANGE

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 socioeconomic, 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.*

2021 Outlook: Charting the Earth's Future

Energy • Managed Resources • Climate • Policy Prospects

The ***2021 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 previous (2018) 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 the impact of the Covid-19 pandemic on economic growth, climate mitigation and public health, as well as the need for a systems approach to climate change and human health and well-being. 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 emissions pathways consistent with these goals.

CONTENTS

About the 2021 Outlook

The 2021 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 the increase in the average global temperature below 2°C or even 1.5°C.

Impacts of the Covid-19 Pandemic

In 2020, Covid-19 captured the world's attention. Throughout the year, the pandemic impacted billions of lives. The massive impact of the virus on lives and economies presents important parallels to the risks and threats we face from human-induced changes to climate. For both challenges, the well-being and survival of our growing and interconnected society hinge on our willingness to confront threats that have global consequences. Key to protecting lives and making our communities more resilient to such threats is an emphasis on proactive, science-based decision-making at all levels of society.

For Covid-19, the scientific process has elucidated the importance and benefits of non-therapeutic measures (e.g. masks, social distancing) to slow transmission and reduce mortality rates from the virus. Yet crucial to reducing the threats, avoiding the risks and averting the dangers, is the societal responsibility to act upon scientific evidence in a timely manner. We have seen encouraging and effective actions with tangible results during the pandemic in several nations and states. Similarly, timely science-based actions are needed to address climate change. However, for climate-related risks, we face a more challenging situation since many of our actions and preparations must be made far in advance, and the benefits are slow to evolve and materialize.

The pandemic has not only served as a teachable moment for how we confront the climate crisis and its impacts on human health, but also for how we manage our economies. Covid-19 has coincidentally given the world an unintended head start on climate action. Since its emergence in late 2019, Covid-19 has substantially reduced economic activities and greenhouse gas emissions resulting from them. While perhaps temporary, a declining trend for emissions is a good sign for reaching our climate goals. However, the negative impacts of the pandemic on economic growth and emergency measures to stimulate national economies provide a complex picture for achieving future decarbonization goals. In slow-growth economies, fewer resources are available for governments to support clean energy alternatives and for private companies to invest in new technologies. In high-growth economies, rising energy demand and prices provide substantial incentives for energy-efficient innovations.

Regardless of the pace of economic development, governments need to intervene to promote a climate sustainability agenda, but resources available for such interventions are highly affected by the Covid-19 crisis. The pandemic has also exacerbated negative trends related to protectionism, populism and nationalism. For a climate problem that requires a global solution, these negative tendencies make efforts to establish global decarbonization pathways even more challenging.

In the 2021 Outlook, we include an assessment of Covid-19 impacts on economic growth, energy and emissions. The Covid-19 pandemic is projected to have a short-term direct impact on greenhouse gas (GHG) emissions. The longer-term effect will be most pronounced if it acts as a catalyst for accelerating the energy transition. Ultimately, government policies and industrial technological leadership will be needed for aggressive GHG mitigation.

Policy Scenarios and Risk-Based Analyses

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 a new 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 ensembles of model 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 2021 Outlook, we focus on four different scenarios. The first, which we call *Paris Forever,* assumes that all Paris Agreement NDCs (as of March 2021) are implemented through the year 2030, and maintained in perpetuity after that. While our *Paris Forever* scenario represents an unprecedented global commitment to limit greenhouse gas emissions, it neither stabilizes climate nor limits climate change.

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	Interngovernmental 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		

We therefore consider two additional scenarios that extend from the Paris Agreement's NDCs and align with its long-term goals. Referred to as *Paris 2°C* and *Paris 1.5°C*, these scenarios aim to limit and stabilize human-induced global climate warming to 2°C and 1.5°C, respectively, by the end of this century. The *Paris 1.5°C* scenario envisions global cooperation that leads to an almost 50% reduction in global greenhouse gas emissions from 2025 to 2030, a highly aspirational projection. We also consider a scenario that's more aggressive in the short-term (up to 2025) but less aggressive in the longer term (2030–2050), which we call *Accelerated Actions.* This scenario is also consistent with the 1.5°C stabilization goal depending on the emissions evolution in the second half of the century.

Online tables for 2020–2050 for our main three scenarios (*Paris Forever*, *Paris 2°C*, and *Accelerated Actions*) are available for each of the individual regions of our EPPA model (see **Box 1** for regional classification details). Please note that all units of measurement are based on the metric system, and all economic values are reported in 2015 US dollars. Our visualization tool explores these scenarios and expands climate outcomes to 2100 for the *Paris Forever, Paris 2°C, and Paris 1.5°C* scenarios.

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/socioeconomic 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 **Box 5**).

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 that incorporates physical and socioeconomic components of climate risks in order to inform decision-making.

Box 1.

Regional Classification Details

The IGSM modeling system and its economic component used to generate the projections in this Outlook divides the global economy into 18 regions (see **Figure 1**). These regions do not align exactly with the G20, the 20 largest economies of the world. For instance, South Africa, Argentina, Saudi Arabia and Turkey are G20 countries, but are also part of various regions that include countries not among the G20. Conversely, Norway, Switzerland, Iceland and Liechtenstein are not G20 members, but are combined with G20 members of the European Union, including France, Germany, Italy and the United Kingdom, as a single region.

A full list of the countries included in each IGSM region is provided in the Appendix and supplementary projection tables for 2020–2050 for the *Paris Forever, Paris 2°C* and *Accelerated Actions* scenarios are available online at: http://globalchange.mit.edu/Outlook2021.

For the reporting in this Outlook, the regions are further aggregated into three broad groups: Developed, Other G20 and Rest of the World. We also created a web-based visualization to explore the main energy-economic and climate results, which is available at: http://globalchange.mit.edu/Outlook2021/Dashboard.

Table 1. IGSM Regional Classification

Regional Group	Abbr.	Region
Developed	**USA**	United States
	CAN	Canada
	EUR	Europe*
	JPN	Japan
	ANZ	Australia, New Zealand and Oceania
Other G20	**CHN**	China
	IND	India
	BRA	Brazil
	RUS	Russia
	MEX	Mexico
	KOR	Korea
	IDZ	Indonesia
Rest of the World	**AFR**	Africa
	ASI	East Asia
	LAM	Other Latin America
	MES	Middle East
	ROE	Other Europe and Central Asia
	REA	Other East Asia

* The European Union (EU-27) plus UK, Norway, Switzerland, Iceland & Liechtenstein

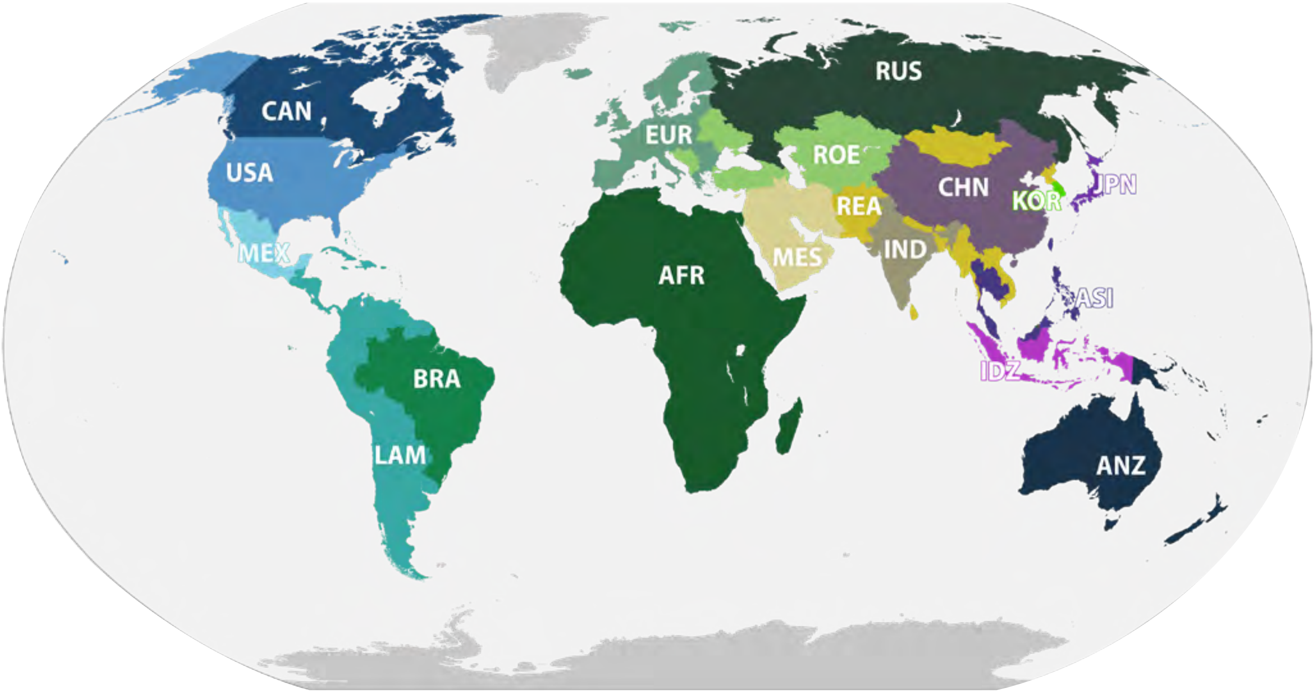

Figure 1. EPPA regions

Key Findings

Here we summarize the key findings of this report based on our modeled projections under three increasingly ambitious greenhouse gas (GHG) emission-reduction scenarios: *Paris Forever, Paris 2°C* and *Accelerated Actions.* In broad terms, these scenarios correspond to maintaining existing climate policies in perpetuity, and capping global warming at 2°C and 1.5°C, respectively, by 2100. More precise scenario definitions are presented in Table 2. 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 *Paris Forever* scenario grows to about 770 exajoules (EJ) by 2050, up by 31% from about 590 EJ in 2020. The share of fossil fuels drops from the current 80% to 70% in 2050. All energy types except coal grow from 2020 to 2050, led by non-biomass renewable energy (wind and solar) with more than a 5.6-fold increase. Natural gas consumption increases by about 50%, hydropower grows by 28% and oil use by 14%. Both nuclear and bioenergy increase by about 3%, while global coal consumption decreases by 7%. Coal's share of primary energy declines from about 26% in 2020 to 18% in 2050.
- In the *Paris 2°C* scenario, global energy use peaks in 2040 at about 660 EJ and then declines to about 635 EJ by 2050. Wind and solar energy grow almost 9 times by 2050 relative to 2020, and natural gas use expands by 25%. Hydropower, bioenergy and nuclear power have similar growth rates as in the *Paris Forever* scenario. In contrast, oil use declines by 40% and coal use by 55% from 2020 to 2050. Coal's share of global primary energy is reduced to 10% in 2050.
- The Paris Agreement pledges made by countries for the year 2030 do not substantially decrease the share of fossil fuels in global primary energy use. From about 80% in 2019, it declines to 74% in 2030. After 2030 it continues to decline, but even by 2050, a majority of global energy comes from fossil fuels in both *Paris Forever* and *Paris 2°C* scenarios. From 2020 to 2050, Covid-19 impacts on energy use and renewable energy deployment are relatively modest (2–4% reduction in energy use each year and virtually the same pathway for renewables relative to the non-Covid trajectory).

Energy-Intensity Improvements

- Our projections show energy-intensity improvements from 2020 to 2050 in all economies. Global energy intensity in the *Paris Forever* scenario is projected to improve at an average annual rate of 2.3% between 2020 and 2050. In the *Paris 2°C* scenario, we project a 2.9% per year improvement during the same periods.

Private Vehicles and Transportation

- From about 10 million electric vehicles (EVs) in 2020, EV stock in the *Paris Forever* scenario reaches 100 million EVs in 2030, almost 300 million in 2040 and nearly 650 million in 2050. With the light-duty vehicle (LDV) stock increasing overall from 1.1 billion in 2020 to about 1.7 billion in 2050, the EV share of the LDV fleet reaches 38% in 2050. EV growth is even faster in the *Paris 2°C* scenario, with a projected 825 million EVs on the road by 2050, comprising 50% of the LDV fleet.
- In the *Accelerated Actions* scenario, the EV stock reaches more than 200 million vehicles in 2030, 600 million in 2040, and more than one billion in 2050. Assuming this accelerated deployment of EVs, two-thirds of all global LDVs by 2050 are electric. Our modeling implies that in achieving a 67% electrification of the global LDV stock, global EV sales would exceed 30 million in 2030, 60 million in 2040, and 100 million in 2050.
- The leaders in EV deployment in all scenarios are China, Europe and USA.

Electricity Production

- Covid-19 decreases global electricity use. In comparison to a world without Covid, our modeling shows about a 4% Covid-induced reduction in electricity production in 2020–2030 and 3% reduction in 2035–2050.
- In the *Paris Forever* scenario, global electricity production (and use) grows by 67% from 2020 to 2050. In comparison to primary energy growth of 31% over the same period, electricity grows twice as fast, resulting in a continuing electrification of the global economy. Generation from variable renewables exhibit the fastest growth, with a 6-fold increase between 2020 and 2050.
- In the *Paris 2°C* scenario, global electricity production grows even faster, rising by 69% between 2020 and 2050. Policies after 2030 lead to a larger growth in variable renewables, which increase 9.7 times from 2020 to 2050.
- Electricity generation from renewable sources becomes a dominant source of power by 2050 in all scenarios. However, intermittency issues are not fully resolved in any region within that time frame, leading to a relatively large share of natural gas in generation.

Energy Prices

- In the *Paris Forever* scenario, the oil price increases by 15% from 2020 to 2050, reaching $67/barrel. In the *Paris 2°C* scenario, this upward trend is reversed by a decrease in oil demand after 2030. The oil price rises to $64/barrel by 2030 and then declines to $45/barrel 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, with China a notable exception.
- The average global electricity price increases from 2020 to 2050 by 16% in the *Paris Forever* scenario and by 26% in the *Paris 2°C* scenario. Price increases are mostly driven by policy requirements to include more low-carbon generation options.

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 without further emissions-reduction efforts, future emissions growth will come from the Other G20 and developing countries, accelerating changes in global and regional temperatures.

Emissions

- Covid-19 impacts on global GHG emissions persist but diminish over time—a 2% reduction by 2025 and about 1% in 2030–2040 below what they would be in a non-Covid world. After that, the difference imposed by the pandemic is less than 1%.

- Global GHG emissions in the *Paris Forever* scenario initially decrease from about 48 gigatonnes of CO_2-equivalent (Gt CO_2e) in 2020 to about 47.5 Gt CO_2e in 2030, and then gradually increase to about 51 Gt CO_2e in 2050 due to growth in countries with less stringent emissions targets. In the *Paris 2°C* scenario, GHG emissions follow the same path as in *Paris Forever* until 2030, and then more aggressive policies reduce them to 34 Gt CO_2e by 2050. In the *Accelerated Actions* scenario, global GHG emissions decline to 20 Gt CO_2e by 2050. Collectively, the world reduces its GHG emissions by almost 60% in 2050 relative to 2020 in that case.
- Extending our projections to 2150, global GHG emissions in the *Paris Forever* scenario continue their gradual increase after 2050 due to global population and GDP growth. Global emissions in the *Paris 2°C* scenario decline to about 10 Gt CO_2e by 2100 and then remain at that level. Two scenarios that stabilize global average surface temperature at 1.5°C relative to pre-industrial levels show emissions starting to decrease in the 2020s. Global GHG emissions in these scenarios decline to about 8 Gt CO_2e by 2100 and then remain at that level. We also tested a scenario where net GHG emissions are set to zero after 2070.

Climate

- Carbon dioxide (CO_2) concentrations in the *Paris Forever* 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 concentrations. In addition, by mid-22nd century, more than half of the IGSM ensemble runs (i.e., at least 50% probability) show CO_2 concentration at double their current level. Also by that time, we project with 100% likelihood that CO_2e concentrations will rise to *at least* double the current level.
- In terms of radiative forcing of climate, our *Paris Forever* scenario aligns 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 attained at 2100. However, in the *Paris Forever* scenario there are 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 (RCP 8.5) by mid-22nd century.
- By 2065, more than half of the IGSM ensemble's *Paris Forever* projections exceed 2°C global climate warming, a fraction that rises to more than 75% by 2071 and more than 95% by 2085. By 2100, 95% of the IGSM projections indicate a global climate warming of at least 2.25°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 2055. By mid-22nd century, the IGSM projections show that the world experiences at least a 3.3°C warming (in 95% of the IGSM ensemble runs) and most likely a warming of 4.1°C (median result).
- The MIT Earth System Model's (MESM's) global hydrologic sensitivity ranges from 1.7–3.3% per °C. In the *Paris Forever* ensemble, the MESM's projected increase in global precipitation between today and mid-century is projected to most likely (i.e., median result) 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 to 0.11 mm/day (or 21,200 km^3/yr)—nearly triple that of the mid-century change.
- In both the *Paris 2°C* and *Paris 1.5°C* scenarios, global temperature will continue to rise through the next two decades. By mid-century, the *Paris 1.5°C* scenario's global temperature will stabilize, while the *Paris 2°C* global temperature will continue to rise through the 2070s. The *Paris 2°C* scenario also indicates that even among all the plausible outcomes captured by the IGSM ensemble, there is no likelihood of even the "coolest" trajectories to remain below 1.5°C at the end of the century. On the other hand, the *Paris 1.5°C* ensemble scenario can virtually assure the world of remaining below 2°C of global-averaged warming.
- The *Paris 2°C* and *Paris 1.5°C* scenarios not only stabilize global precipitation increase (by 2060 in *Paris 1.5°C*, and by 2100 in *Paris 2°C*), but substantially reduce the magnitude and potential range of increases. *Paris 2°C* cuts the increases in half and *Paris 1.5°C* reduces them to almost a third of the *Paris Forever* global precipitation changes. The hydrologic sensitivity of total precipitation from heavy and extreme precipitation events can be 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 reduction in both flood risk and 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 *Paris Forever* 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, 3.6 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 *Paris Forever* 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 basins experiencing compounding societal and environmental pressures on water resources.
- Population projections under combined water stress in all scenarios reveal that the most aggressive climate target (i.e., the 1.5°C scenario) can reduce approximately 60 million of the additional 680 million people projected to be living in water-stressed basins in 2050 compared to today. Over 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 observe 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 *Paris Forever* scenario, overall food production increases by 90% from 2020 to 2050, crop production by 70% and livestock production by 81%. Livestock production grows faster than crop production due to higher shares of protein-rich food in diets when income rises. Food production grows faster than livestock and crop production.
- Under the *Paris Forever* scenario, technological change and changing agricultural management practices result in greater yields, which prevent high increases in prices. By 2050 food prices are only 2% higher than in 2020. Crop prices rise a bit more (7%), while livestock prices rise by 42% and forest products by 33%.
- Under the *Paris 2°C* scenario, the value of crop output is 1.5% lower than in the *Paris Forever* scenario, while livestock output reduces by 1.9% and food output by 2.3%. Changes in prices are also quite modest, but a bit more discernable than changes in output. Prices of livestock products initially increase, declining later by 4% by 2050 compared to the *Paris Forever* scenario, while prices of food products and crop products decrease by 5.4% and 2.8% respectively.

Land-Use Change

- Global land-use projections from 2020 to 2050 are quite stable. Natural forest areas decrease by 1% and natural grasslands by 3%. These are converted mostly to cropland areas, which increase by 7%, while pasture lands increase by only 0.14%.
- Acreage dedicated to biomass for energy increases by 38%, but as it occupies only 2.9% of the total cropland area in 2020, it remains relatively small in 2050 (3.7% of the total cropland area). By 2100, cropland area is only 2.3% larger than in 2020, while pasture land is 0.44% larger. Natural for-

ests and natural grasslands decrease by 2% and 4% by 2100, respectively. Biomass area increases by 126% compared to the 2020 area to cope with the growth of bioenergy output, but the total biomass area covers only 6% of total cropland.

- Land-use changes in the *Paris 2°C* scenario are similar to those in the *Paris Forever* scenario by 2050, but quite different by 2100. By that time, the area dedicated to bioenergy output reaches 17% of total cropland area, while it is only 6% in the *Paris Forever* scenario. Cropland area increases by 22%, while pastureland decreases by 31% to give room for cropland and bioenergy expansion.

Meeting Short-Term Paris Commitments

Key countries and regions are progressing in fulfilling their Paris 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 its 2020 Emissions Gap Report, the UN Environmental Program (UNEP) evaluated the emissions control packages of the G20 nations, grading each for adequacy. Thirteen of the 20 were projected to meet their NDCs with currently implemented policies, which collectively account for around 60% of 2020 GHG emissions. Five, including the U.S., were judged to need additional measures, and insufficient information was available to evaluate the remaining two.
- Our estimate of economic growth to 2030 and beyond, compared to the pre-pandemic projection show that Covid-19's GDP impact will, for many nations, lower the economic cost of the measures required to fulfill their NDCs. Taken all together, microeconomic effects of Covid-19 appear to further ease the burden of meeting existing Paris pledges.
- Harder to judge is the effect of the current economic downturn and associated political disruption on the priority nations will give to the climate threat and their Paris pledges. Also unknown is what will happen to next steps in implementation of the Paris Agreement. On the other hand, there are encouraging signs of commitment by several of the largest greenhouse gas emitters.
- Accounting for the pandemic's effect on economic growth and assuming all nations meet their NDCs under these conditions, the result is stabilization of global GHG emissions through 2030. With the prospect that Covid-19's effects may lower the effort required to meet existing pledges, and the announced increase in ambition by several large emitters, it is likely that the world's collective efforts will not only achieve this level of emissions control by 2030, but exceed it.

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 in general 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 2021 Outlook. The remaining report describes the details behind these broad conclusions.

Box 2.

New in the 2021 Outlook

Policy scenarios

In addition to *Paris Forever*, our main scenario from the previous Outlooks, we explore two scenarios of increased mitigation ambition, *Paris 2°C* and *Accelerated Actions*. For all three scenarios, we provide Excel files with main economic, energy, emission and land-use results for all 18 regions of our Economic Projection and Policy Analysis (EPPA) model.

Extended horizon for climate modeling

We extend the modeling and report climate results up to 2150.

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 changes include updates to the base-year economic dataset, projections of gross domestic product (GDP) and population growth, technology costs, and the Earth-system response to changing emissions and concentrations. In addition, our MESM downscaling procedure incorporates the latest information from the Coupled Model Intercomparison Project Phase 6 (CMIP6).

Impacts of Covid-19

We incorporate estimates of Covid-19 impacts into our projections of economy, energy, emissions and climate.

Web-based tool for visualization of Outlook results

We have created a web-based tool http://globalchange.mit.edu/Outlook2021/Dashboard for visualization of the major economy, energy and emissions results for all 18 regions of the EPPA model for three scenarios: *Paris Forever, Paris 2°C* and *Accelerated Actions*. We also provide global climate results for these scenarios.

Greenhouse Gamble Wheels

We add a short description of the Greenhouse Gamble Wheels, our tool for communicating uncertainty related to temperature implications of policy scenarios. Additional information about the wheels can be found at: https://globalchange.mit.edu/research/research-tools/risk-analysis/greenhouse-gamble.

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 (UN, 2019). According to this estimate, the global population grows from 7.8 billion people in 2020 to 9.7 billion in 2050, and to 10.9 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 Other G20 region, population grows from 3.6 billion in 2020 to 3.9 billion in 2050 and then declines to 3.3 billion by 2100. In contrast, population in the Rest of the World continues to increase from 3.1 billion in 2020 to 4.7 billion in 2050, and to 6.5 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 40% in 2020 to 50% in 2050, and to 60% in 2100.

For near-term economic growth projections (up to 2030, including impacts from Covid-19), we rely on our recent analysis (Reilly *et al.*, 2021); for medium-term projections (up to 2050), we use OECD (2020) and IEA (2020) forecasts. 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% in 2020–2050, slowing to 2.2% per year for the period 2050–2100. Growth is slower in the Developed region, rising at 1.8% throughout the century. The Other G20 region grows at 3% per year in 2020–2050 and at 2.1% in 2050–2100. The Rest of the World grows at 3.5% in 2020–2050 and at 2.9% thereafter.

In contrast to population, most of the global economic value in 2020 was in the Developed region, a trend that persists throughout the century (**Figure 3**). Despite the higher economic growth in non-Developed regions, their shares of global GDP catch 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 15% in 2020 to 20% in 2050, and to 30% in 2100. This result illustrates the remaining inequality among world regions in per capita income.

Our projections show that Covid-19 will have a lasting impact on global GDP (**Figure 4**). We estimate that global annual average GDP growth between 2015 and 2020 would have been 2.9% in a world without Covid, but that value was reduced to 1.2% due to the negative shock of Covid-19. The negative impact on GDP in 2020 is 8%, which is the sum of a 5% loss compared to the 2019 level and about 3% of expected global growth in 2020 that did not occur. The post-2020 world GDP grows, but at a slower pace than the pre-Covid rate. For the years 2025–2050, we project that global GDP will remain about 3–4% below what it would be in a world without Covid.

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 energy and land-use policies, which 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 as of March 2021 (In April 2021, several countries announced new targets for 2030 with increased emissions-reduction efforts, but those announcements have not yet been submitted as official NDCs). Considerable interpretation is required to represent in our modeling system the approximate effect of policies and measures on emissions levels. (**Box 3**).

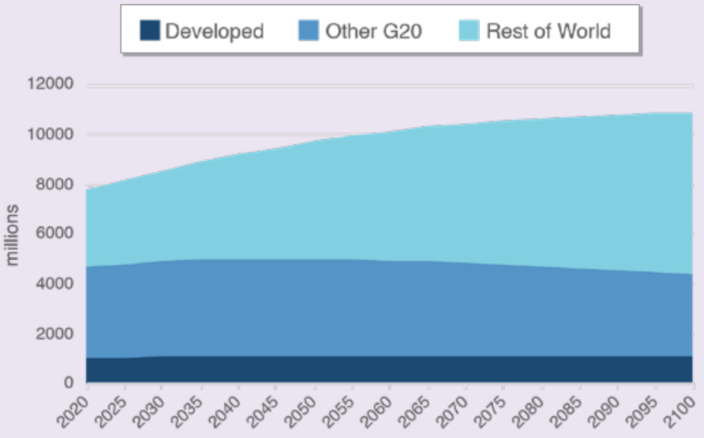

Figure 2. World population

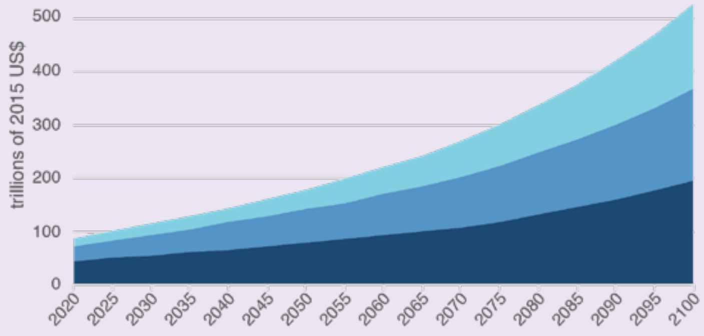

Figure 3. World GDP

In this Outlook, we focus on the following three scenarios:

- *Paris Forever*, which assumes implementation of commitments under the Paris Agreement by 2030 (as described in Box 3) and continuation of those policies thereafter, with no additional policy action;
- *Paris 2°C,* which assumes policy action beyond current Paris commitments to ensure that the increase in Earth's average surface temperature (relative to pre-industrial levels) does not exceed 2°C. We assume mitigation is achieved through global economy-wide carbon pricing after 2030.
- *Accelerated Actions*, in which countries impose more aggressive emissions targets. We include new targets, announced by the USA, Canada and Japan in April 2021, and additional emissions reductions by other countries that represent an illustrative pathway of significantly increased mitigation.

The *Paris Forever* scenario evaluates the pledges that countries have made in their NDCs specified for 2030, commitments we assume will be maintained after 2030. While it is desirable to start aggressive GHG mitigation as soon as possible, we believe that the 2030 NDC pledges represent participating countries' current level of ambition in the context of the Paris Agreement. Therefore, in the *Paris 2°C* scenario, we assume these pledges are implemented up to 2030. However, in this scenario we also assume that an agreement is reached to implement a globally coordinated climate policy aimed at deep emission reductions after 2030 consistent with the stabilization of the global average atmospheric temperature at 2°C above pre-industrial levels with a probability of 50%.

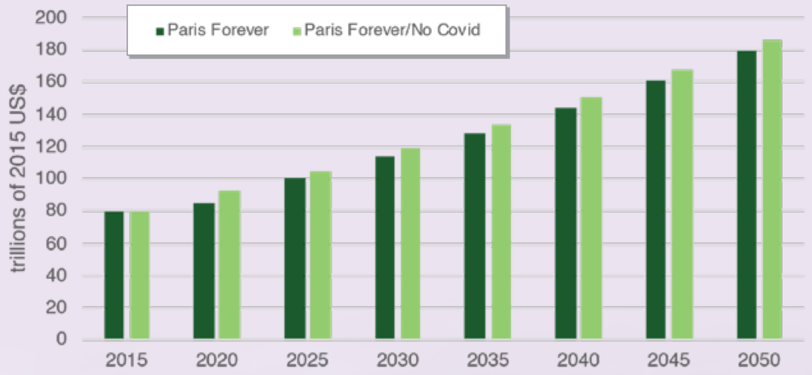

Figure 4. Impact of Covid-19 on the World GDP

Table 2. Outlook Scenarios

Scenario	Description
Paris Forever	Current (as of March 2021) Paris Nationally Determined Contribution (NDC) targets are met by all countries by 2030 and retained thereafter
Paris 2°C	Paris Nationally Determined Contribution (NDC) targets are met by all countries by 2030, after which there is an emissions cap based on a global emissions trajectory designed to ensure that the 2100 global surface mean temperature does not exceed 2°C above pre-industrial levels with a 50% probability
Accelerated Actions	More near-term actions are taken relative to *Paris 2°C* (including those planned changes to NDCs announced in April 2021), and global emissions are consistent with ensuring that the 2100 global surface mean temperature does not exceed 1.5°C above pre-industrial levels with a 50% probability. Note: Climate results are shown for a slightly different 1.5°C scenario (*Paris 1.5°C*) that uses a global emissions price.

In addition, we explore an *Accelerated Actions* scenario in which countries impose much more aggressive emission targets. This scenario includes the new goals for 2030 that were announced in April (USA reduces by 50-52% relative to 2005 emission levels, Canada reduces by 40-45% relative to 2005, Japan reduces by 46% relative to 2013) and targets for other countries that are stricter than those submitted in their current NDCs. As a result, we assume that global GHG emissions in 2030 are lower by almost 20% in comparison to the global implications of the current (as of March 2021) NDC pledges for 2030. In this scenario, nations continue on the accelerated path after 2030 and countries in the Developed regional grouping reduce their 2050 GHG emissions by 80% relative to their 2005 levels. Most of the countries in the Other G20 reduce their 2050 GHG emissions by 50% with respect to 2005 levels (except for India and Indonesia (30%) and Russia (40%)). In the Rest of the World, Africa and the Rest of East Asia end up in 2050 at their 2015 GHG levels, while other countries reduce their GHGs in 2050 by 50% relative to 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.

To evaluate the temperature implications of the *Accelerated Actions* scenario, we extended the scenario beyond 2050 in two ways. In the first variant, emissions decline until they reach almost zero by 2070 and stay at that level thereafter. In the second variant, the post-2050 world moves to an emission trajectory consistent with the stabilization of the global average atmospheric temperature at 1.5°C. For climate implications, we also consider a *Paris 1.5°C* scenario that achieves the long-term goal of the Paris Agreement of limiting the temperature to 1.5°C above pre-industrial levels with a probability of 50% (as described in Morris *et al.*, 2021).

Our Outlook scenarios are summarized in **Table 2**.

More Information

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Box 3.

NDCs under the Paris Agreement & Implementation of Policies in Our Projections

Our 2020–2030 emissions projections in the *Paris Forever* and *Paris 2°C* scenarios are based on Paris Agreement Nationally Determined Contributions (NDCs) submitted (as of March 2021) to the UN Framework Convention on Climate Change (UNFCCC), and summarized in **Table 3**. We assess these NDCs, implementing them at the country/region level of our EPPA model. Many countries describe emissions reduction targets relative to an absolute (ABS) level of emissions defined by an historical level such as 2005. Europe and Russia continue to use 1990 as the base year.

Other countries, such as China and India, describe targets based on emissions intensity (INT). For countries with NDCs included within larger EPPA regions, we assess how their targets would affect emissions for the region as a whole relative (REL) to business-as-usual (BAU), and summarize the combined effects in the final column of the table as a percentage reduction of CO_2e from the identified base for each country/region, or in terms of energy intensity reductions for regions that have chosen emissions intensity as a goal (see Jacoby *et al* (2017) for details).

The U.S. returned to the Paris Agreement in 2021, and in April 2021 the U.S. administration announced a specific target for 2030 of reducing emissions by 50-52% relative to the 2005 level. This announcement has not yet been submitted as a formal NDC. In the Paris Forever and Paris 2°C scenarios, for USA we impose a 36% GHG emissions reduction in 2030 relative to 2005 levels. We test an alternative target for USA of a 52% GHG emissions reduction in 2030 relative to 2005 levels in the *Accelerated Actions* scenario. Similarly, for Canada and Japan we impose newly announced goals (40% reduction relative to 2005 for Canada, and 46% reduction relative to 2013 for Japan) in the *Accelerated Actions* scenario. In this scenario, we also impose a stricter target for the EU, where in 2030 it reaches a 55% reduction relative to 1990 levels, instead of 45% assumed in the other scenarios that reflect a potential use of offsets. Other countries' increases in the assumed mitigation actions in the *Accelerated Actions* scenario are not based on the formal NDC announcement, but are considered for illustrative purposes.

The electric power sector is the largest single source of greenhouse gas emissions in most individual countries, and globally as well. Many policy and control measures are applied to this industry, but the most significant in terms of emissions reduction and cost are those aimed at driving out coal and promoting renewables.

Coal-Fired Generation. Many nations are imposing policies that include shutting down existing coal-fired generation. Following Jacoby *et al* (2017), for USA, CAN, EUR JPN and MEX, we assume that no new units will be added after 2015, and that existing capacity will be retired at age 60. The resulting reduction in 2025 to 2030 is shown in **Table 4**. The results indicate the advanced age of the coal fleet, particularly in USA and EUR. China pledges to cap coal use "around" 2030. No policies directed at coal use in electric generation are assumed in IND and MES.

Renewable Energy Policies. Many countries are promoting solar and wind generation through renewable energy mandates and various forms of subsidy, and often state these measures in their NDCs. Renewable sources of generation receiving policy attention include hydroelectric sources, biofuels and tidal and wave power, but the main focus is on solar and wind. We apply renewable targets based on IEA (2020).

Transport. Policies in the light-duty vehicle sector and commercial transport are generally applied in the form of efficiency standards for new vehicle sales as described in Jacoby *et al* (2017) and Reilly *et al* (2021).

Table 4. Policies directly applied to coal-fired electricity. Additional policies may reduce coal use further.

Region	Capacity Reduction in 2030 (% of 2015)	Other Features
USA	40	
CAN	25	
EUR	35	
JPN	10	
CHN	NA	Cap 2035 & 2040 at 2030 level
IND	NA	No coal constraint
MEX	30	
MES	NA	No coal constraint

Table 3. NDCs and Assumed Performance in 2030 in *Paris Forever* and *Paris 2°C* Scenarios

Region	NDC		CO_2e 2005 Mt or t/$1000	Other Features	Expected CO_2e reduction[1]
	Type/Base	Reduction			
USA	ABS 2005	26-28% by 2025	6600	Alternative 2030 target (announced Apr 2021) tested in *Accelerated Actions*	36% in 2030
EUR	ABS 1990	55% by 2030	5720 for EU-28 (1990)	EUR in EPPA includes EU-28 and other European countries. Alt. 2030 target (55% without offsets) tested in *Accelerated Actions*	45%
CAN	ABS 2005	30% by 2030	820	Mainly land use & forestry with 18% reduction in industrial. Alt. 2030 target (announced April 2021) tested in *Accelerated Actions*	25%
JPN	ABS 2013	26% by 2030	1320 (2015)	2.5% LUCF. Nuclear = 20–22% of electric, solar/wind = 9%, also biomass. Assumes ITMOs. Target = 1.04b ton CO_2e. Alt. 2030 target (announced Apr 2021) tested in *Accelerated Actions*	26%
ANZ	ABS 2005	26-28% by 2030	596		20%[2]
BRA	ABS 2005	37% by 2025	2.19	45% of primary energy renewable by 2030; LUCF down 41% 2005–2012	35%
CHN	CO_2 INT 2005	60-65% by 2030	2.55	CO_2 peak by 2030, Non-fossil 20% of primary energy	55%
KOR	BAU	37% by 2030	NA		25%
IND	INT 2005	30-36% by 2030	2.29	2.5–3.0b tons CO_2 from forests. 40% non-fossil electric. Assumes un-specified financial assistance.	30%
IDZ	BAU	29% by 2030	NA	Role of LUCF (63% of current emissions) unclear. Industrial emissions increase.	30%
MEX	BAU	25% by 2030	NA	22% of CO_2, 51% of BC, Intensity reduction of 40% 2013–2030.	25%
RUS	ABS 1990	25-30% by 2030	3530	Reduction subject to "maximum accounting" from forests.	32%
ASI	BAU		NA	Malaysia 45% INT, Philippines 70% BAU, Thailand 20% BAU, Singapore ABS 36%	10%
AFR	BAU		NA	Nigeria 45% BAU, South Africa 20–80% increase (ABS), limited information on other regions.	5%
MES	BAU		NA	Saudi & Kuwait actions only, Iran 15% BAU, UAE non-GHG actions	10%
LAM	BAU		NA	Argentina 15% BAU, Chile 35% INT, Peru 20% BAU, Colombia 20% BAU	10%
REA	BAU		NA	Bangladesh 5% BAU, Pakistan reduction after unspecified peak, Sri Lanka 7% BAU, Myanmar & Nepal misc. actions	10%
ROE	BAU		NA	Azerbaijan 13% BAU, Kazakhstan 15% 1990, Turkey 21% BAU, Ukraine 40% BAU	10%

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[1] Percentage applies to the particular target in column 2.

[2] Expectation discounted by political reversals in AUS.

Perspective: Economic and Policy Impacts of Covid-19

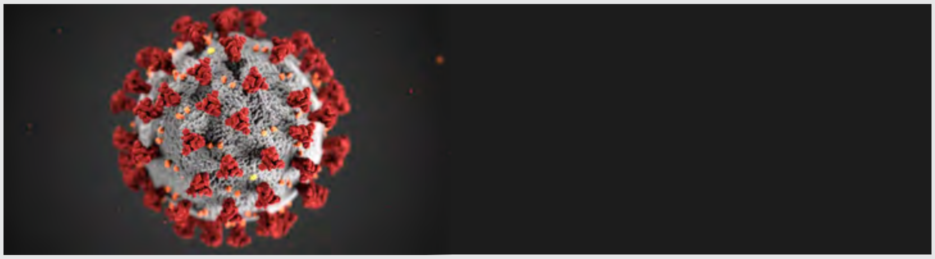
Richard Schmalensee, Professor of Management and Economics Emeritus, MIT Sloan School of Management

The short-run consequences of Covid-19 have dominated world news since March 2020. We have seen overcrowded hospitals and relentlessly mounting death tolls. Many people are enduring long-term unemployment, and many more are quietly suffering high levels of stress, anxiety and depression. Familiar businesses fail daily, and millions face eviction and homelessness. Wealthy households are saving money by reducing spending on such things as travel and restaurant meals, while poor households continue to spend every nickel they can earn. And earning those nickels often involves exposure to the virus. There have been sharp reductions in commercial and industrial energy use during the pandemic, along with very modest reductions by households as more adults work from home and more children attend school from home. Overall, carbon dioxide emissions from wealthy countries have fallen substantially during the pandemic.

This largely bleak picture won't change significantly until the pandemic is behind us. The U.S. still has high levels of infection in some regions, and restrictions on economic activity may be re-imposed where necessary to save lives. The longer the pandemic lasts, the more serious will be the long-term damage to the economy from business failures, foreclosures, compromised education, long-term unemployment, and supply chain disruptions. Full recovery will take a long time once the pandemic ends. Replacing failed businesses and destroyed supply chains will be hard enough, but it may never be possible to fully repair the damage to individuals and families.

Post-pandemic energy use and emissions

In the post-pandemic recovery, energy use will surely rebound in the absence of major policy changes, and carbon dioxide emissions will increase. Demand patterns appear likely to change in predictable directions but not in easily predictable magnitudes. For instance, many people will have worked from home for a substantial period of time, and some will have spent much of the pandemic away from urban areas. It seems unlikely that all will return to the old regime of daily commutes from suburban homes to crowded offices in city centers. The demand for commercial office space seems likely to decline, but by how much is unknowable.



More broadly, some behaviors and attitudes shaped by the pandemic will endure, at least in part, but some will not. It is difficult now to imagine returning to crowded public transportation, for instance. To the extent that this attitude persists, the importance of public transportation relative to autos may decline. We've gotten used to Zoom meetings, and business travel seems unlikely to return to previous levels. Travel for tourism will be difficult until the pandemic has passed everywhere, and wealthy households may become habituated to doing less of it. Alternatively, there may be an eruption of pent-up demand for leisure travel when it again becomes safe.

Overall, my guess is that in the absence of major emissions-reducing policy changes, energy use and CO_2 emissions per dollar of GDP will decline slightly as a consequence of the pandemic. (Luckily, it will be very hard to measure that impact with any precision, so my guess is unlikely to be decisively proven wrong!)

Climate policy implications

I think the pandemic is more likely to have postponed major emissions-reducing policy changes than to have encouraged them. After a period of widespread economic hardship, it is hard to imagine great enthusiasm for economic sacrifices to slow climate change—or for any other purpose. At least for the next several years, many governments may succumb to the temptation to treat the short-run emissions reductions caused by the pandemic as justifying delaying further emissions-reducing actions.

Major emissions-reducing policy changes seem especially unlikely in the U.S. While the Democrats captured the White House last November and retained a slim majority in the House of Representatives, the Republicans have enough votes in the Senate to block any major legislative initiative from the Biden White House. Moreover, history suggests that the Democrats will lose seats in the House and Senate in 2022 and perhaps lose majorities in both. While the Biden White House will almost certainly restore something like the Obama administration's Clean Power Plan by rule-making and will make a large number of smaller changes in policies and procedures by Executive Order, serious climate legislation appears very unlikely to pass for at least the next four years. The only possibility would seem to be a version of the Administration's recent climate-oriented infrastructure Bill, slimmed down so it can be passed by a simple majority in the Senate. This would not be a Green New Deal.

The story at the state level may be different. In the absence of federal action, many states have taken the lead in decarbonizing electricity. Only 12 of the 50 states lack some sort of commitment to renewable or clean (renewable plus nuclear) electricity. A recent UCLA study found that around a third of U.S. citizens live in jurisdictions that are committed to 100% clean or renewable electricity by around 2050. Even in the absence of further policy changes, aggressive decarbonization of electricity generation will be required by those commitments for decades to come.

These ambitious state programs rely on subsidies, not taxes or regulations. Sellers of electricity to its ultimate consumers are required to buy clean/renewable electricity, and they pay a premium to secure those supplies. Those subsidies are paid for by raising retail rates, which rarely vary much over time. While decarbonization is a laudable goal, even if this approach succeeded in fully decarbonizing electricity generation, it would only cut around 30% of U.S. greenhouse gas emissions.

More important, these programs, as designed, generally work against decarbonizing the whole economy. Studies of economy-wide decarbonization conclude that the efficient path involves decarbonizing electricity generation and using clean electricity to replace fossil fuels in other sectors. In decarbonized electric power systems that rely heavily on wind and solar generation, the marginal cost of electricity will vary more than it does today, and it will be very low much of the time. If that variation is reflected in retail rates, consumers will have incentives to use electricity heavily when it is very cheap, and that will facilitate economy-wide electrification. The road the activist states are on, in contrast, involves raising the retail price of electricity at all times. Raising retail rates at all times will inhibit economy-wide electrification and thus work against economy-wide decarbonization.

Energy

Primary Energy Use

Context

Energy consumption is vital for human well-being and ubiquitous in our daily lives. We depend on it for everything from meal preparation to climate control to transportation to powering our digital devices. Consequently, energy-related emissions are by far the largest contributor to human-caused greenhouse gases (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 2019, about 80% of global primary (i.e., pre-processed) energy consumption was based on coal, oil and natural gas. As the population grows and energy demand rises, improving energy efficiency and transitioning to lower-carbon energy sources (e.g., wind, solar, biomass, hydro and nuclear) will be needed to ensure sustainable economic growth.

Key Findings

Our models show that Covid-19 will have a small but notable impact on global energy use over the next three decades (**Figure 5**). We estimate that global energy use in 2020 was 4% lower due to the pandemic, and project that it will remain about 2–3% below what it would be in a world without Covid in the years 2025 to 2050. Several regions have introduced recovery packages that include provisions for low-carbon energy investments, but they are not included in our projections. If those packages prove effective, they might further accelerate deployment of low-carbon energy sources, particularly in the EU and USA.

We project that global primary energy use in the *Paris Forever* scenario will grow to about 770 exajoules (EJ) by 2050, up by 31% from about 590 EJ in 2020 (**Figure 6**). In this estimate we include commercial fuels and traditional biomass use. The share of fossil fuels (coal, oil, gas) drops from the current 80% to 70% in 2050. In absolute values, all energy types except coal are growing from 2020 to 2050. Variable renewable energy (wind and solar) leads this growth with more than a 5.6-fold increase. Natural gas consumption is about 50% larger, hydropower grows by 28% and oil use by 14%. Both nuclear and bioenergy increase by about 3%, while global coal consumption decreases by 7%. Coal's share of primary energy declines from about 26% in 2020 to 18% in 2050.

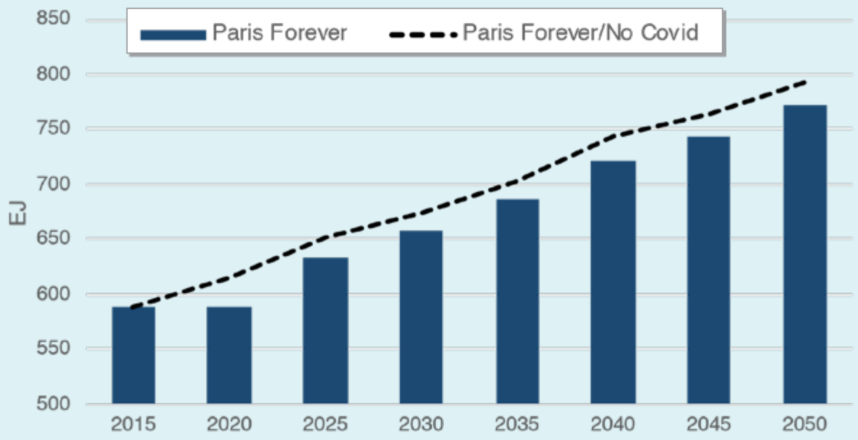


Figure 5. Global Energy Use (exajoules) in the *Paris Forever* scenario: with Covid-19 (blue bars) and without Covid-19 (dashed line)

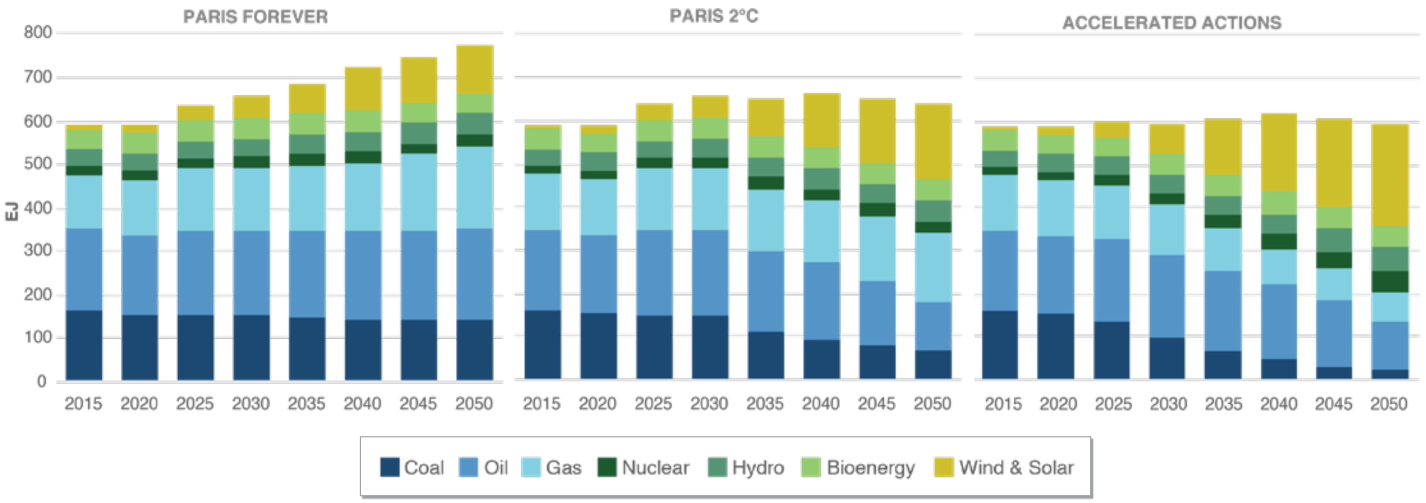


Figure 6. Global Energy Use (exajoules) in the *Paris Forever* (left), *Paris 2°C* (center), and *Accelerated Actions* (right) scenarios.

Global energy use in the *Paris 2°C* scenario follows a different trajectory. While, by design, the results up to 2030 are the same as in the *Paris Forever* scenario, policies and measures in the 2°C scenario are accelerated after 2030. Global energy use peaks in 2040 at about 660 EJ and then declines to about 635 EJ by 2050. Price- and policy-driven energy efficiency measures play a substantial role in reducing annual consumption. In this scenario, wind and solar energy grow almost 9 times by 2050 relative to 2020, and natural gas use expands by 25%. Hydropower, bioenergy and nuclear power have similar growth rates as in the *Paris Forever* scenario. In contrast, oil use declines by 40% and coal use by 55% from 2020 to 2050. Coal's share of global primary energy is reduced to 10% in 2050. The *Accelerated Actions* scenario squeezes out fossil fuels further.

Primary energy use has different trajectories in the Developed, Other G20, and Rest of the World regions. In the *Paris Forever* scenario (**Figure 7**), energy consumption stays roughly constant in the Developed region, while in the Other G20 and Rest of the World it grows by about 40% from 2020 to 2050. Coal and oil use decline in the Developed region, while in the Other G20, coal use remains about the same and oil use slightly increases. Whereas in the *Paris Forever* Scenario, coal and oil use still increase in the Rest of the World, our *Paris 2°C* scenario projection (**Figure 8**) shows a decline in coal and oil use in all regions after 2030.

Implications

The Paris Agreement pledges made by countries for the year 2030 do not substantially decrease the share of fossil fuels in global primary energy use. From about 80% in 2019, it declines to 74% in 2030. After 2030 it continues to decline, but even by 2050, the majority of global energy comes from fossil fuels in both *Paris Forever* and *Paris 2°C* scenarios. Increased ambition for 2030 targets and acceleration of decarbonization post-2030 will be required to achieve larger reductions in fossil fuel use. From 2020 to 2050, Covid-19 impacts on energy use and renewable energy deployment are relatively modest (2–4% reduction in energy use each year and virtually the same pathway for renewables relative to the non-Covid trajectory). Thus, additional policy actions will be needed to speed up the energy transition towards low-carbon sources.

More Information

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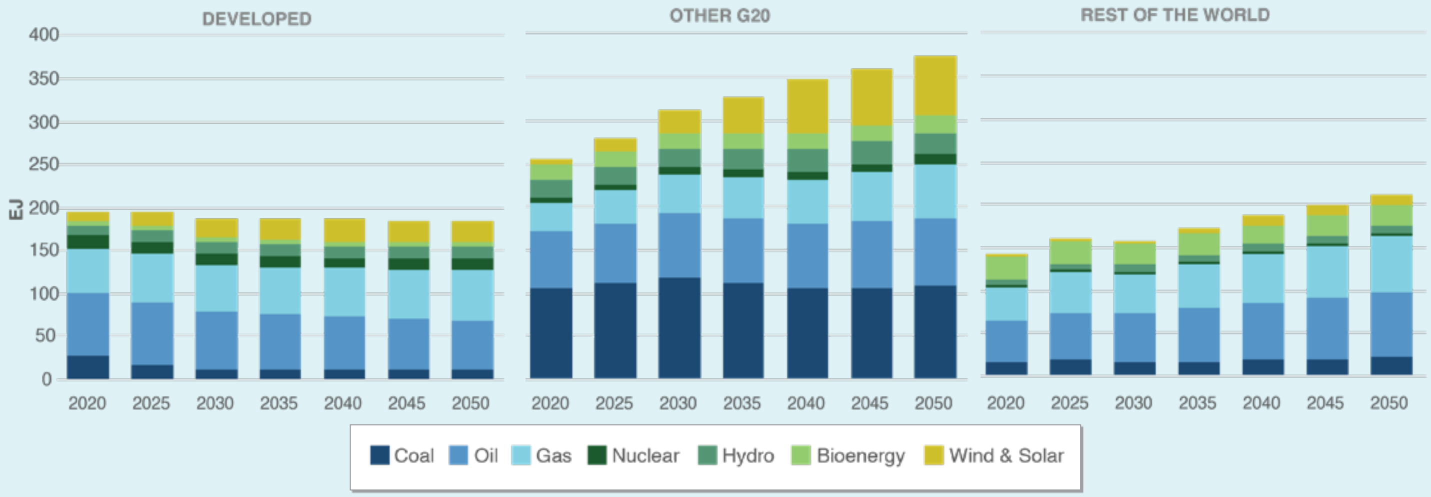

Figure 7. Energy Use (exajoules) in the *Paris Forever* scenario by major group: Developed (left), Other G20 (center), Rest of the World (right)

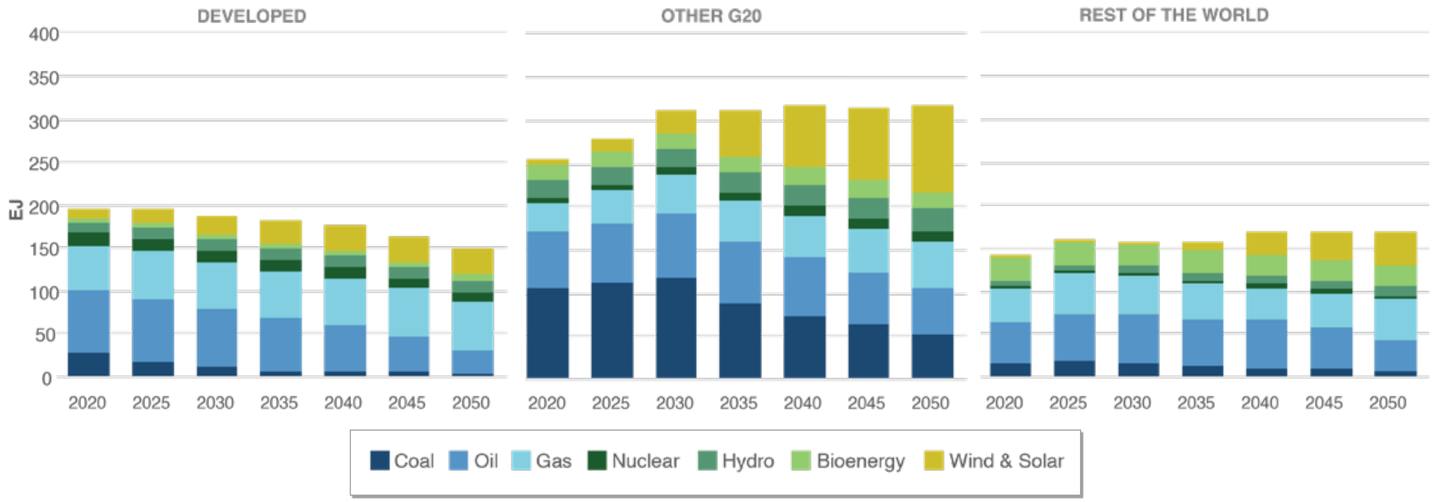

Figure 8. Energy Use (exajoules) in the *Paris 2°C* scenario by major group: Developed (left), Other G20 (center), Rest of the World (right)

Regional Energy Intensity Improvements

Context

A measure of the energy efficiency of an economy, energy intensity is defined as the number of units (e.g., exajoules) of energy per unit (e.g., dollars, in the case of the U.S.) 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, energy imports and cost of living, among other things. 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. 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

Our projections show energy-intensity improvements from 2020 to 2050 in all economies. In the *Paris Forever* scenario (**Figure 9**), Canada is the most rapidly improving country in the Developed regional grouping; its energy intensity improves at an annual average rate of 3.3%. USA and Australia/New Zealand (ANZ) improve at 3.2%, while the rates in Europe and Japan are 2.4% and 2.8%, respectively. In the Other G20 group, Indonesia and India lead the way with the rates 3.6% and 3.5%, respectively. Brazil and Korea improve at 3%, and China and Mexico at 2.8%. Russia is projected to have the slowest rate of improvement (1.8%) throughout the three-decade period. For the Rest of the World, Africa and Other East Asia improve faster than other regions, at 3.9%. The regions of Other Latin America, East Asia and the Middle East improve at 2.8–3%. The improvements in Other Eurasia are the slowest in this Rest of the World regional group at 2.2%. Overall, global energy intensity in the *Paris Forever* scenario is projected to improve at an average annual rate of 2.3% between 2020 and 2050.

In the *Paris 2°C* scenario, the general tendencies are similar, but more aggressive climate policies lead to faster energy-intensity improvements. Globally, we project a 2.9% improvement from 2020 to 2050 in this scenario. Climate policies especially accelerate improvements in Africa, Australia/New Zealand (ANZ) and Korea (**Figure 10**), where the rates increase to 4.4–4.8%. The factors driving this acceleration include structural change, technological change, rising energy prices, and the rate of economic growth. Faster growth means higher investments, hence 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. With no efficiency gains, the world in 2050 would need to produce 60% more energy in the *Paris Forever* scenario and 80% more energy in the *Paris 2°C* scenario. Accelerating investments in energy efficiency will be critical to avoid depletion of natural resources and transition to more sustainable and environmentally-friendly development.

More Information

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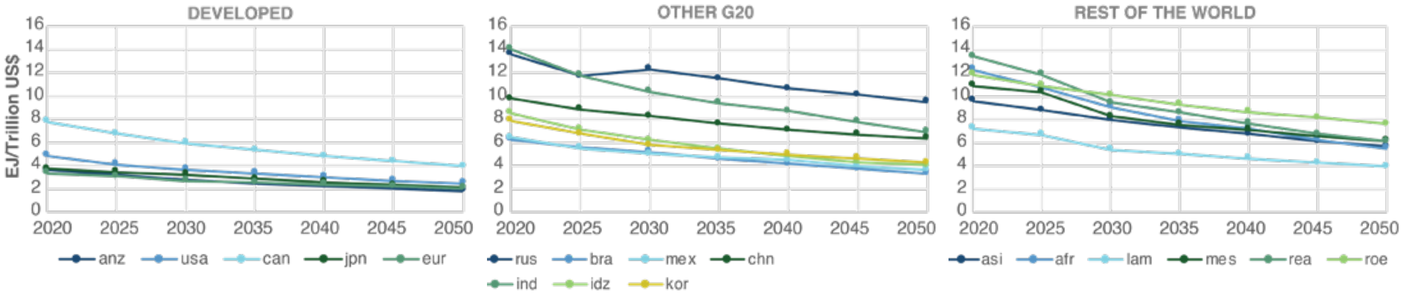


Figure 9. Energy Intensity (EJ/trillion US 2015$) in the *Paris Forever* scenario by major group: Developed (left), Other G20 (center), Rest of the World (right)

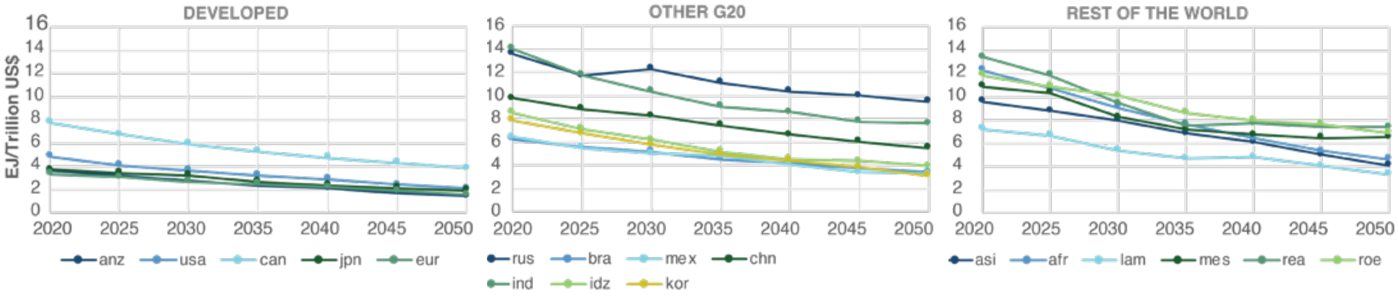


Figure 10. Energy Intensity (EJ/trillion US 2015$) in the *Paris 2°C* scenario by major group: Developed (left), Other G20 (center), Rest of the World (right)

Electrification of Light-Duty Vehicles

Context

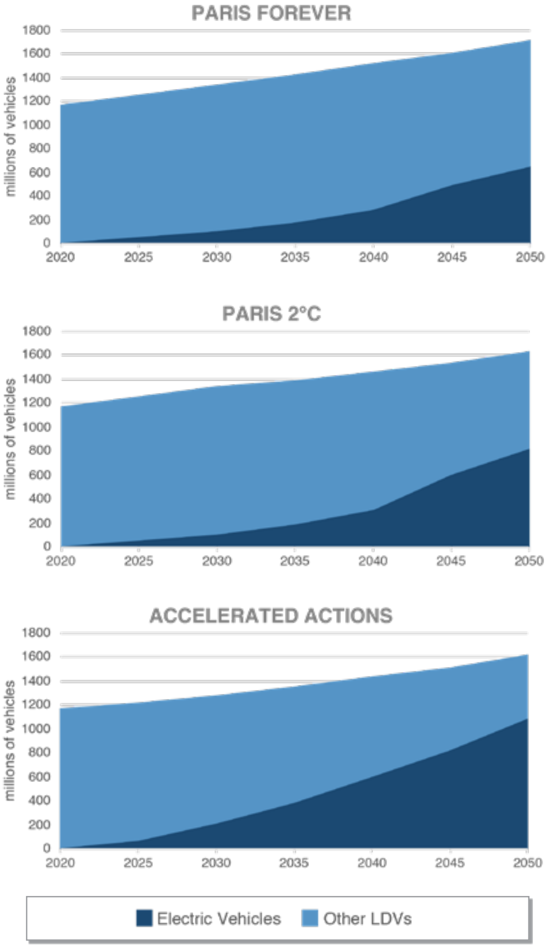
Electric vehicles (EVs) offer a solution for decarbonizing the transportation sector. Household private light-duty (i.e., cars and light trucks) vehicles (LDVs) are well-suited for electrification because of their smaller size and battery requirements compared to commercial vehicles that transport heavier loads. As the electricity sector turns increasingly to clean energy sources, EVs will help to reduce both GHG emissions and air pollution. Several car manufacturers and local and regional governments have declared ambitious targets for EV deployment in the next 10–15 years, but achieving LDV decarbonization on a large scale will be a formidable challenge.

In the MIT Mobility of the Future study (MIT, 2019), we helped quantify the size of the current global LDV fleet (1.1 billion vehicles) and future scenarios for its growth. Currently, the EV fleet (battery-electric and plug-in-hybrid vehicles) is rather small, with about 10 million vehicles at the end of 2020—less than 1% of the total LDV fleet. Last year EV sales set a new record with about 3 million vehicles sold globally (see **Box 4** for an assessment of the pandemic's impact on EV sales). With annual global LDV sales of about 100 million vehicles, substantial expansion of EVs will be needed to achieve decarbonization goals.

Key Findings

We estimate a rapid increase in the global EV stock over the next three decades. From about 10 million EVs in 2020, the EV stock in the *Paris Forever* scenario reaches 100 million EVs in 2030, almost 300 million in 2040 and nearly 650 million in 2050 (**Figure 11**, top). With the LDV stock increasing overall from 1.1 billion in 2020 to about 1.7 billion in 2050, the EV share of the LDV fleet reaches 38% in 2050. EV growth is even faster in the *Paris 2°C* scenario, with a projected 825 million EVs on the road by 2050 (Figure 11, middle), with 50% of the LDV fleet electric. To achieve this level of EV fleet penetration, 80% of all cars sold globally in 2050 must be electric. For additional details about these scenarios, see MIT (2019).

We also explore a scenario (*Accelerated Actions*) with more aggressive global mitigation actions including accelerated support for EVs. In this scenario, EV stock reaches more than 200 million vehicles in 2030, 600 million in 2040, and more than one billion in 2050 (Figure 11, bottom). Assuming this accelerated deployment of EVs, two-thirds of all global LDVs by 2050 are electric. Our modeling implies that to achieve a 67% electrification of the global LDV stock, global EV sales would exceed 30 million in 2030, 60 million in 2040, and 100 million in 2050. While we have not evaluated the amount


PARIS FOREVER

PARIS 2°C

ACCELERATED ACTIONS

Figure 11. EV contribution to the global LDV stock (millions of vehicles) in the *Paris Forever* (top), *Paris 2°C* (middle) and *Accelerated Actions* (bottom) scenarios

Box 4

Impact of Covid-19 on EV Sales

By Lucy Young, MIT student

The Covid-19 pandemic and subsequent government policies substantially impacted global electric vehicle (EV) deployment in 2020. In the first half of 2020, global EV sales were down by 15% relative to their corresponding 2019 levels due to lockdowns and shutdowns of EV manufacturing facilities in several countries. However, in the second half of 2020, EV sales recovered and started to surpass the corresponding 2019 monthly sales as governments with low-carbon goals devoted parts of their stimulus funds to support the EV industry. The greatest support for EVs came from European countries, notably Germany and France, which increased EV subsidies by up to 100%. Though less generous than in Europe, China also demonstrated support for EVs by extending existing EV subsidies. In contrast, the U.S. in 2020 provided little additional support to EVs.

Globally, December 2020 set an all-time monthly record of close to 600,000 electric vehicles sold. Overall, it is estimated that in 2020 about 3 million EVs sold, which is 40% more than in 2019 despite the pandemic. This year-on-year growth from 2019 to 2020 is significantly greater than the 2018–2019 total, which was only about 10%. Countries that took a more aggressive approach to increasing incentives for purchasing EVs experienced greater growth in EV sales. For example, Germany's decision to double existing subsidies for individual EV purchases led to a 263% increase in annual sales. What governments can learn from this experience is that stimulus packages can be effective tools to promote climate-change mitigation goals.

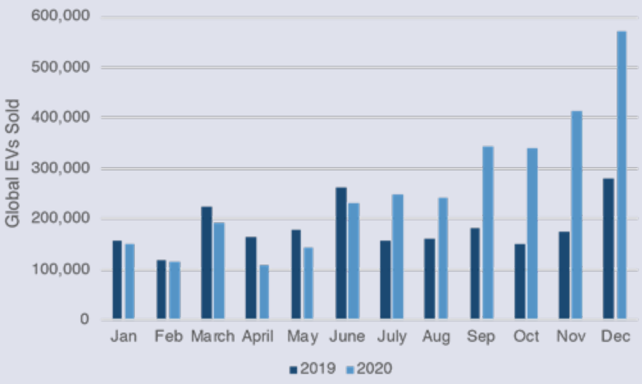


Figure 12. Global monthly sales of electric (battery and plug-in hybrid) vehicles. Data source: ev-sales.blogspot.com

and availability of materials needed for battery production to support these levels of car manufacturing, it is clear that new supply chains and technologies will be critical for sustained growth in EV deployment.

Our projections of EV deployment by major regional groupings (**Figure 13**) show that growth will be led by the Developed (driven by Europe and USA) and Other G20 (driven by China and India) regions. We estimate that in 2030 the Developed region has the most EVs (about 60 million vehicles in *Paris Forever* and *Paris 2°C* scenarios, and about 120 million vehicles in the *Accelerated Actions* scenario), but by 2050 the EV markets in the Developed and Other G20 regions are roughly the same size (260–270 million vehicles in the *Paris Forever*, 330–350 million in the *Paris 2°C* and 425–465 million in the *Accelerated Actions* scenario) because other countries in the Other G20 region (Mexico, Brazil, Russia, Korea, Indonesia) are also projected to substantially accelerate their electrification efforts by mid-century.

The leaders in EV deployment in all scenarios are China, Europe and USA (**Figure 14**). In the *Paris Forever* scenario, we estimate that China's electric fleet grows from 4.5 million in 2020 to about 25 million in 2030, and to about 130 million in 2050. In the *Accelerated Actions* scenario, China's EV stock reaches 50 million in 2030 and 250 million in 2050. Europe has comparable growth by 2030 (from the current 2.4 million EVs in 2020), but then grows slower than China. Europe's EV fleet in 2050 is about 100 million in the *Paris Forever* scenario and about 200 million in the *Accelerated Actions* scenario. The EV deployment trajectory in the USA is similar to Europe's. India's LDV fleet is projected to be smaller than in China, Europe or the USA, but its EV growth is also remarkable, reaching about 50–60 million of electric vehicles by 2050.

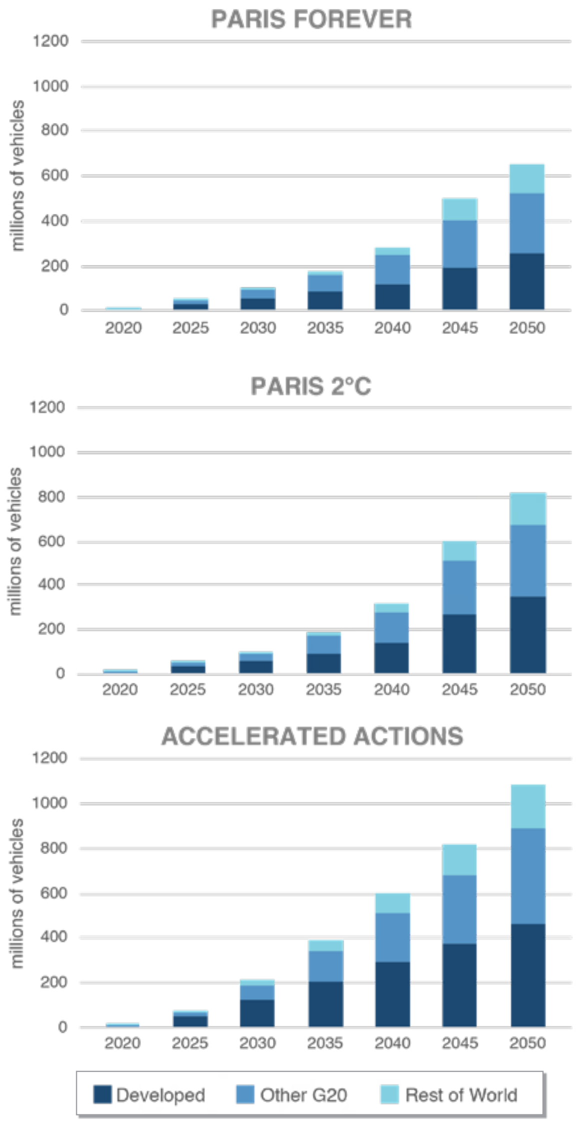


Figure 13. EV deployment by major regional group: *Paris Forever* (top), *Paris 2°C* (middle) and *Accelerated Actions* (bottom) scenarios

Implications

Electrification of light-duty vehicles is growing rapidly in all scenarios. By mid-century, EVs occupy a large share of fleets in all world regions with major market growth in China, Europe and the USA. Meanwhile, the need for mobility expands substantially. While electrification of LDVs can contribute significantly to mitigating GHG emissions in the transportation sector, it offers only a partial solution. A comprehensive solution will require not just one technology but an integrated system approach that includes more efficient internal-combustion vehicles, a long-term switch to low- and net-zero carbon fuels for transport, and increased efficiency of the transport system through digitalization, smart pricing and multi-modal integration. Additional emissions reductions could come from more consumers shifting from private transportation to low-emitting public transport, shared mobility, biking and walking.

More Information

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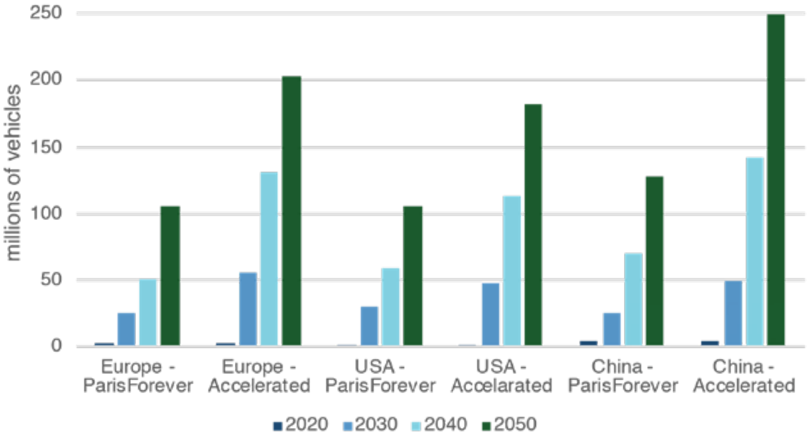

Figure 14. EV deployment in Europe, USA and China in the *Paris Forever* and *Accelerated Actions* scenarios

Electricity Production

Context

Decarbonizing electricity generation is usually regarded as one of the first steps toward an economy with net-zero GHG emissions. Declining costs of wind and solar power make this step economically feasible. With clean electricity generation and accelerated electrification of transport, buildings and industry, substantial decarbonization of the economy can be achieved. To date, growth in electricity demand has been met by installing both fossil and non-fossil sources. But in the coming decades, successful resolution of intermittency issues for variable renewables (wind and solar) will likely create a path for rapid decarbonization efforts. 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

We project that the impact of Covid-19 on electricity will be similar to its impact on primary energy use. Covid-19 slows down global electricity use. In comparison to a world without Covid, our modeling shows about a 4% Covid-induced reduction in electricity production in 2020–2030 and 3% reduction in 2035–2050.

In the *Paris Forever* scenario (**Figure 15**, top), global electricity production (and use) grows by 67% from 2020 to 2050. In comparison to primary energy growth of 31% over the same period, electricity grows twice as fast, resulting in a continuing electrification of the global economy. Generation from variable renewables exhibits the fastest growth, with a 6-fold increase between 2020 and 2050. Biomass-based electricity production rises by about 70% and hydroelectricity by about 40%. The combined share of these renewables in electricity production increases from about 30% in 2020 to about 50% in 2050. Growth in nuclear generation is about 10%. Oil-fired generation is small in 2020 and decreases further over time. We project substantial switching from coal to natural gas generation, with coal decreasing by almost 40% and natural gas increasing by 105% between 2020 and 2050.

In the *Paris 2°C* scenario (Figure 15, middle), global electricity production grows even faster, rising by 69% between 2020 and 2050. Policies after 2030 lead to a larger growth in variable renewables, which increase 9.7 times from 2020 to 2050. The switch away from coal accelerates after 2030, with coal decreasing by 81% between 2020 and 2050. Natural gas increases by 47% during that time. We have also tested a scenario (*Accelerated Actions*) with more aggressive global mitigation actions (Figure 15, bottom), in which the share of renewables in total electricity production in 2050 reaches 78%. In this scenario, coal- and oil-based generation are virtually eliminated by mid-century. Natural gas generation declines by 32% from 2020 to 2050, while variable renewables grow 13-fold over that period of time. This scenario shows the importance of enhancing decarbonization efforts.

Electricity production for major regional groupings in the *Paris Forever* scenario is shown in **Figure 16**. In the Developed group, over the 2020–2050 period, coal generation quickly declines and renewables grow, while natural gas generation mostly stays flat. In the Other G20 group, the coal decline is smaller while growth in renewables is more aggressive. In the Rest of the World, renewables also grow, but natural gas remains the main option. In the *Paris 2°C* scenario (**Figure 17**), the general trends are similar. The main difference is a faster decline in coal and rise in renewable generation in all regions. In this scenario, most of the growth in renewables occurs in the Other G20 group, primarily due to the fast growth of renewables in China and India.

Implications

Electricity generation from renewables becomes a dominant source of power by 2050 in all 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 our main scenarios, intermittency issues are not fully resolved in any region in the next two to three decades, leading to a relatively large share of natural gas in generation. We also project that natural gas expands the most in regions with less aggressive mitigation policies (Africa, the Middle East, Other East Asia). To ensure a transition to low-carbon power generation in less economically developed regions, rich countries will need to provide sufficient technology transfer and financial support to incentivize further decarbonization.

More Information

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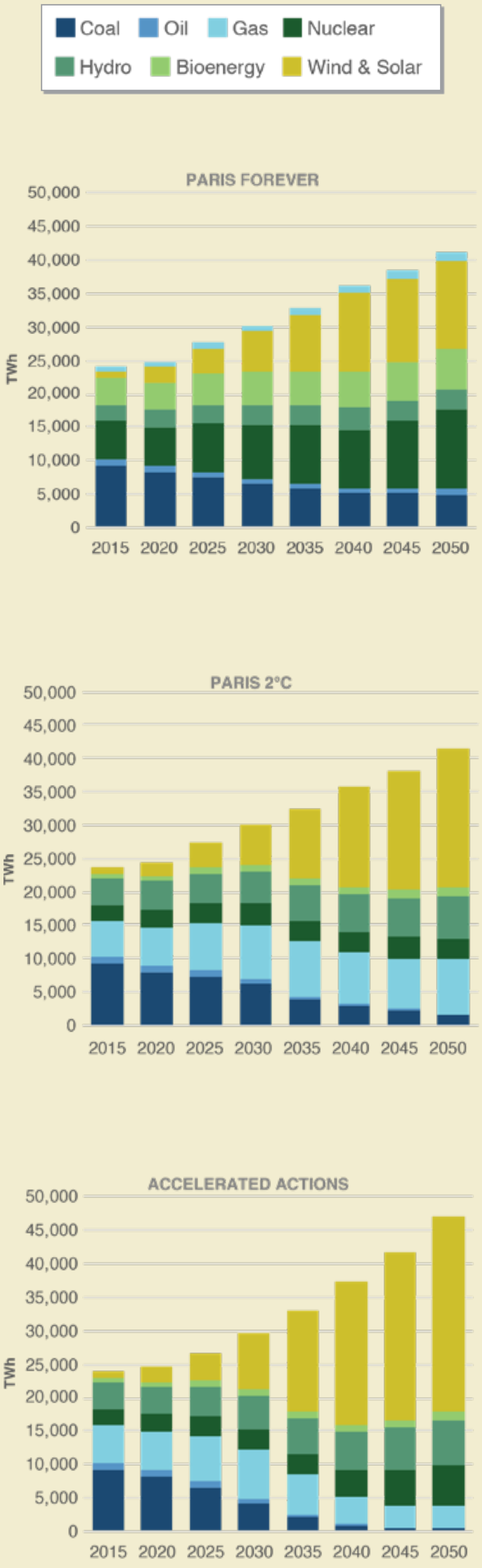


Figure 15. Global electricity production (terawatt-hours, TWh) in the *Paris Forever* (top), *Paris 2°C* (middle) and *Accelerated Actions* (bottom) scenarios

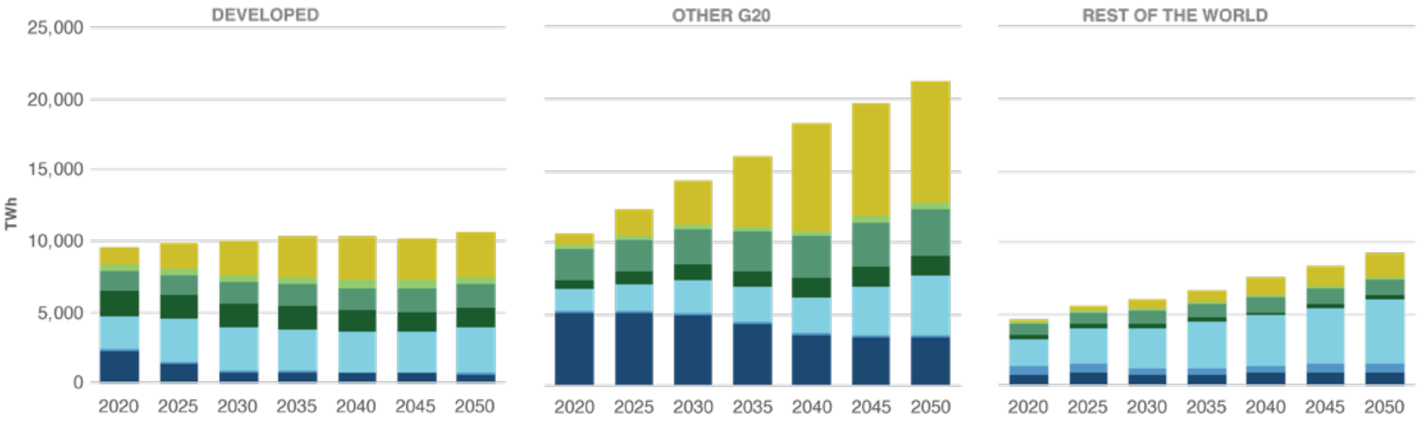


Figure 16. Electricity production (terawatt-hours, TWh) in the *Paris Forever* scenario by major group: Developed (left), Other G20 (center), Rest of the World (right)

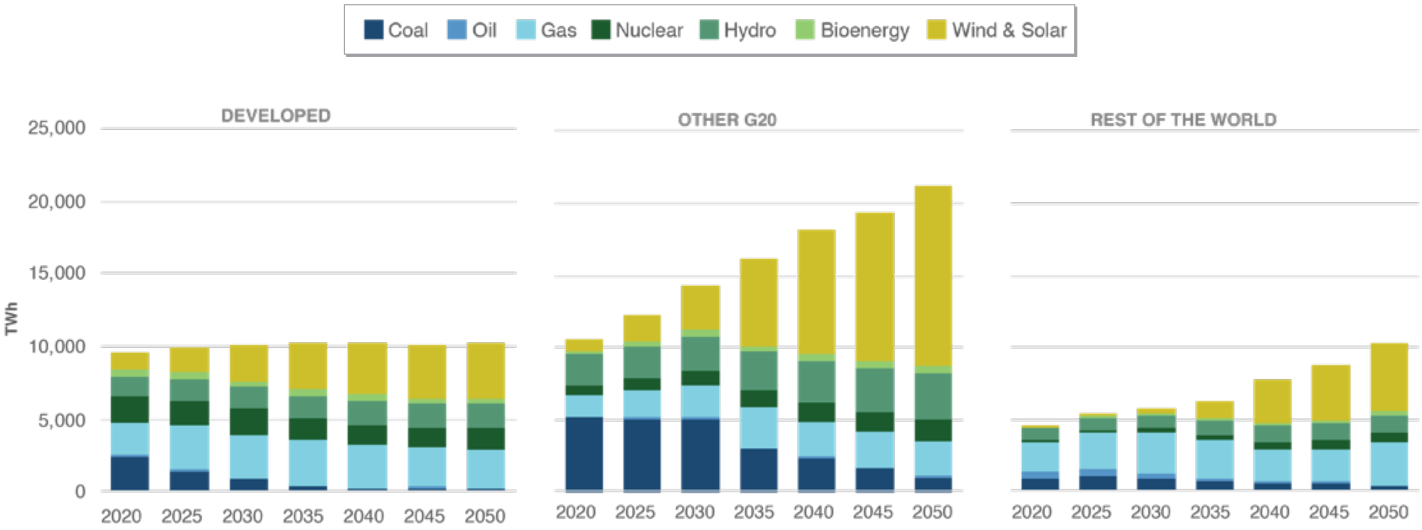
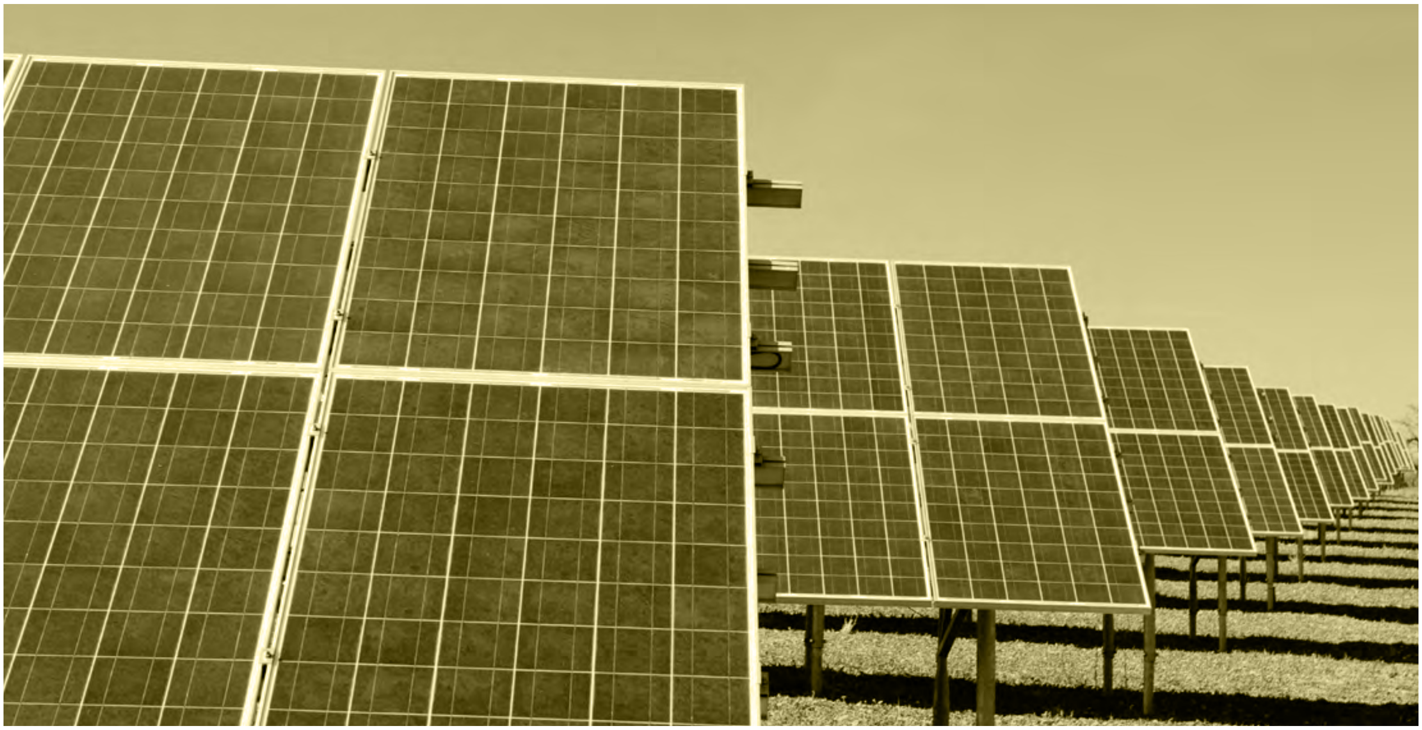


Figure 17. Electricity production (terawatt-hours, TWh) in the *Paris 2°C* scenario by major group: Developed (left), Other G20 (center), Rest of the World (right)



Energy Prices

Context

Energy prices are highly variable from year to year and subject to periodic large swings, sometimes sharply dropping within months and then increasing back to earlier levels. The Covid-19 pandemic reduced demand for economic activities, resulting in a decrease in energy prices, but recovered energy consumption is now pushing prices back up.

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 a five-year period. 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 price indices for all commodities explicitly represented. These price indices are then converted to price levels based on the corresponding historic prices in the base year.

Key Findings

Our modeling projects a slow increase in the crude oil price in the *Paris Forever* scenario (**Table 5**). The average oil price in 2020 was about $40/barrel, but the average prices in 2018 and 2019 ranged from $65 to $70/barrel. We project a recovery of oil prices in 2021–2022, so that the five-year average around 2020 is $59/barrel. In the *Paris Forever* scenario, the oil price increases by 15% from 2020 to 2050, reaching $67/barrel. This increase is driven by resource depletion: as more oil is used over time, further development of potentially more expensive resources is needed. In the *Paris 2°C* scenario, this upward trend is reversed by a decrease in oil demand after 2030. The oil price rises to $64/barrel by 2030 and then declines to $45/barrel in 2050. In this scenario, global oil consumption drops from about 200 EJ in 2030 to about 115 EJ in 2050. While prices that oil producers receive for their products are decreasing, consumer prices are affected by taxes, standards and other policies. The equivalent carbon price in the *Paris 2°C* scenario rises from about $50/tCO$_2$ in 2035 to about $145/tCO$_2$ in 2050, which in turn increases the price of oil faced by consumers.

Natural gas prices vary by region. In the USA, we project a rather stable price of around $3/MBtu in both scenarios. Increased demand for natural gas to replace coal-based power generation results in a slight upward trend in U.S. natural gas prices. In Europe, natural gas prices grow from $6.68/MBtu in 2020 to $7.20/MBtu in 2050 in the *Paris Forever* scenario, but they decrease to $6.59/MBtu in 2050 in the *Paris 2°C* scenario due to substantial expansion of renewables and the virtual elimination of natural gas from power generation. China also expands renewables, but still relies heavily on natural gas in many sectors of its economy. Its natural gas prices rise from $8/MBtu in 2020 to $8.33/MBtu in the *Paris Forever* scenario and to $8.66/MBtu in the *Paris 2°C* scenario.

Coal prices also vary by region, and we project declining prices in most regions due to reductions in demand for coal. China is a notable exception. In the *Paris Forever* scenario, coal use in China is somewhat reduced, but it is still sizeable and broadly used in many sectors, creating the need for new mining activities. In the USA, coal prices fall from $50/tonne of steam coal in 2020 to $42/tonne in 2050 in the *Paris Forever* scenario and $35/tonne in 2050 in the *Paris 2°C* scenario. In Europe, the corresponding price changes are from $58/tonne in 2020 to $51/tonne and $43/tonne, respectively, in 2050.

Electricity prices are growing in both scenarios. While the changes differ by region, the average global electricity price increases from 2020 to 2050 by 16% in the *Paris Forever* scenario and by 26% in the *Paris 2°C* scenario. Price increases are mostly driven by policy requirements to include more low-carbon generation options. Also, in many developed countries, this requirement is coupled with overcapacity of old generation plants that are now producing at prices that would not 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.

Implications

Climate policy reduces the appeal of fossil fuels. While natural gas may see some increases in demand due to its lower carbon content relative to coal and oil, its use (unless coupled with carbon capture and storage technology) will likely decrease under more aggressive emissions mitigation policies. Under the *Paris Forever* scenario, demand for fossil fuels remains substantial, and corresponding global energy prices increase. In the *Paris 2°C* 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.

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Table 5. Fossil fuel prices in different scenarios

	Region	Scenario	2020	2025	2030	2035	2040	2045	2050
Crude oil ($/barrel)	World	ParisForever	59	63	64	65	66	66	67
	World	Paris 2C	59	63	64	62	60	53	45
Natural gas ($/Mbtu)	USA	ParisForever	2.95	3.04	3.06	3.04	3.01	2.98	2.97
		Paris 2C	2.95	3.04	3.06	3.09	3.08	3.04	3.06
	Europe	ParisForever	6.68	6.91	6.96	7.00	7.07	7.14	7.20
		Paris 2C	6.68	6.91	6.96	6.90	6.83	6.68	6.59
	China	ParisForever	8.00	8.32	8.62	8.54	8.51	8.43	8.33
		Paris 2C	8.00	8.32	8.62	8.54	9.08	9.19	8.86
Coal ($/tonne)	USA	ParisForever	50	45	41	41	42	42	42
		Paris 2C	50	45	41	37	36	35	35
	Europe	ParisForever	58	55	53	52	51	51	51
		Paris 2C	58	55	53	50	48	47	43
	China	ParisForever	87	89	92	91	89	91	93
		Paris 2C	87	89	92	84	79	74	71

Managed Resources

Water

Context

The availability of water is fundamental to the health and long-term viability of the billions of people who share this planet. While the Earth's weather and climate systems drive the continual replenishment of fresh water to our rivers and aquifers, we routinely rely on managed water systems to sustain human lives and livelihoods. Climate change, population growth and increased socio-economic activity all have direct effects on the pressure placed on these systems. Influenced by these three factors, water shortages will have profound impacts on human health, political instability and environmental sustainability in the coming decades. We must therefore use state-of-the-art analytic tools to identify emerging and compounding risks to water-stress threats across the world's major river basins, whether driven by natural or human causes, and determine suitable adaptive measures to reduce those risks at scale.

Key Findings

We have assessed 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. We have combined two important metrics of water stress: 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 through optimal allocation of its water supply. For each of our Outlook scenarios, we have tracked these two metrics at every WRS basin (282 globally) and have assessed the total population concurrently affected by both of these water stress measures.

Under the *Paris Forever* scenario (**Figure 18**), we find that 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, 3.6 billion people will be living within basins exposed to environmental water stress. We also find that 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 *Paris Forever* 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 compounding societal and environmental pressures on water resources will be experienced.

To what extent could aggressive climate actions alleviate these conditions and on what scale must we consider adaptive measures? Across the Outlook scenarios, projections of the population under combined water stress (**Figure 19**) reveal that the most aggressive climate target (i.e., the 1.5°C scenario) can reduce approximately 60 million of the additional 680 million people projected to be living in water-stressed basins in 2050 compared to today. We further find that over 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.

Implications

While we observe 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. World-

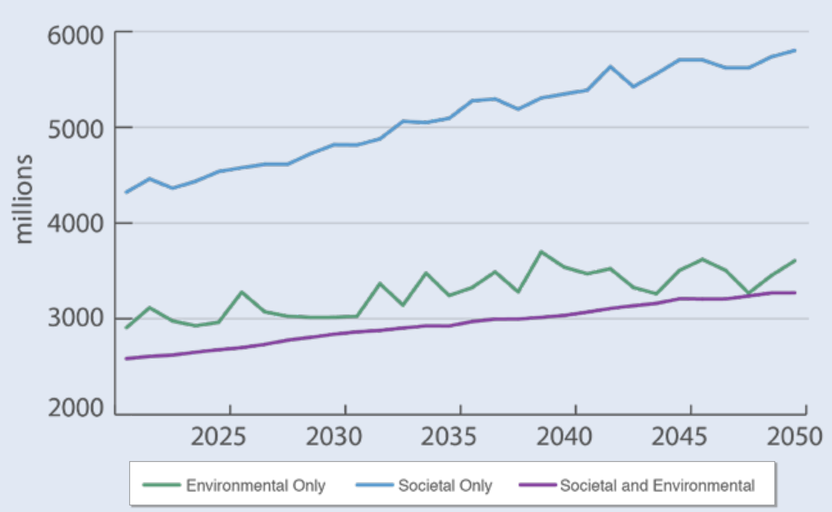

Figure 18. Global population exposed to individual and compounding societal and environmental threats of water stress under the *Paris Forever* scenario

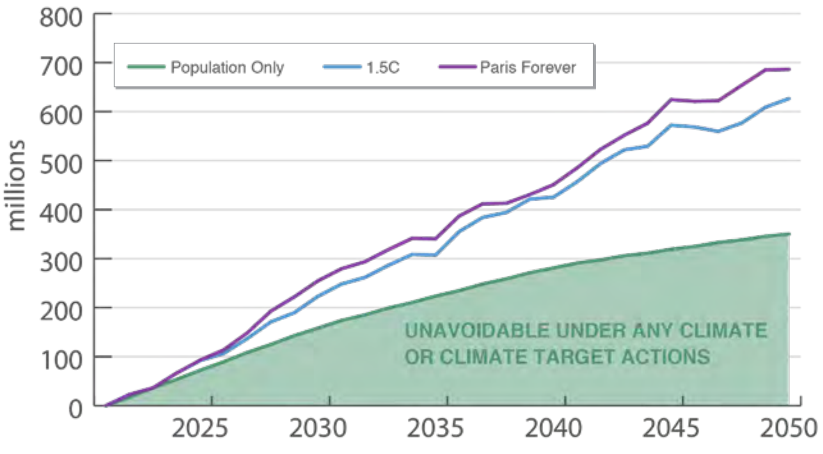

Figure 19. Change in global population that will be exposed to compounding societal and environmental threats of water stress relative to the current exposed population level

wide increases in population, economic growth and associated water demands are largely a challenge of sustainability—one that can only be alleviated through widespread transformations of water systems' storage capacity, conveyance and water-use efficiencies. Since all of these transformations cannot be achieved simultaneously, any concerted, global effort toward water sustainability must be prioritized so that decision-makers confront those basins that face unprecedented and/or the most salient threat in the coming decades. To that end, we have constructed a global map (**Figure 20**) that depicts an overall "threat score" of water risk across the world's major river basins represented by the WRS projections. High-priority basins or regions include: the Arabian Peninsula, Brahmaputra, Danube, Huang He, Indus, Ganges, Murray-Darling, Niger, Nile, Rio Grande, Southern Mediterranean, Volta and the Zambezi.

More Information

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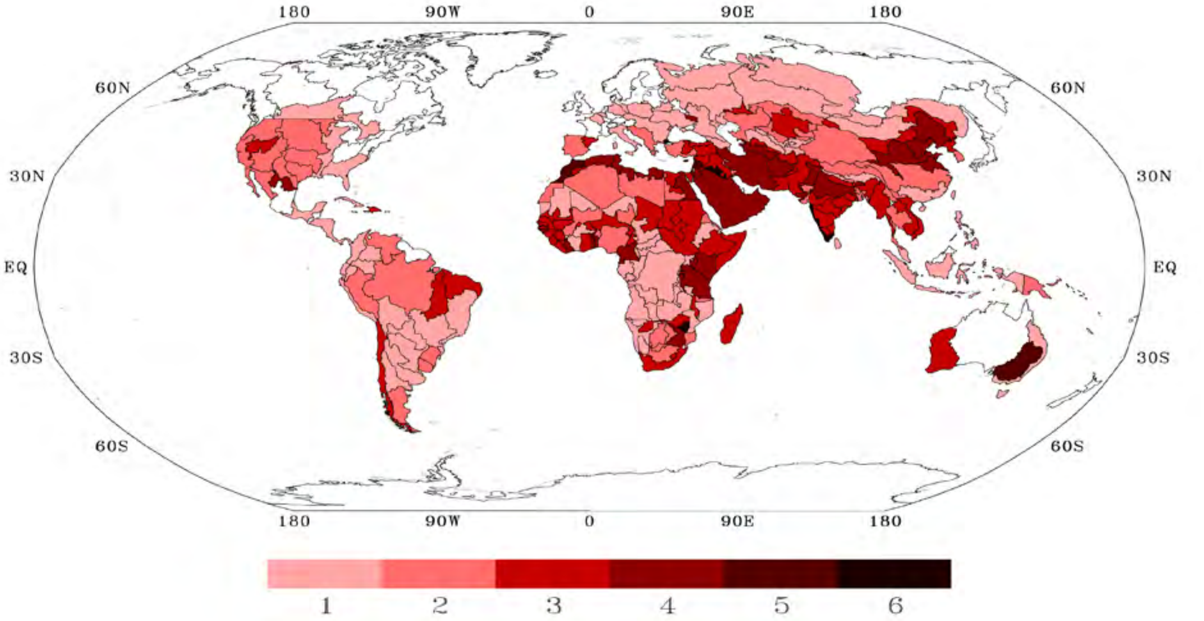

Figure 20. Global map of an aggregate water-stress threat indicator that shows whether three conditions are met in both societal and environmental water stress indices: 1) a positive trend through the 2021-2059 period; 2) water-stress conditions occur for more than half of the period between 2021-2059; and 3) the index does not indicate stressed conditions across 2010-2019 but they emerge by 2050-2059. A value of 6 indicates that all these conditions are met for both societal and environmental water stress (highest threat). Areas not shaded indicate none of the conditions are met for either of the stress indices.

Agriculture

Context

The agriculture sector significantly impacts our society and environment, which, at the same time, impact the sector itself. For example, natural resources such as land and water are used intensively as inputs in agricultural activities, which, in turn, substantially affect those resources. Moreover, population and economic growth, changing diets, and crop and livestock productivity are major drivers of food supply and demand. These drivers shape future trends of agricultural and food production, and their impacts on greenhouse gas (GHG) emissions and land-use change.

Key Findings

We project that in the *Paris Forever* scenario overall, food production will increase by 90% from 2020 to 2050, crop production by 70% and livestock production by 81% (**Figure 21**). Population growth leads to some increase in food and agricultural demand, but economic growth and higher income are the major drivers: while world population grows by only 25%, global GDP will be 109% higher by 2050. Livestock production grows faster than crop production due to higher shares of protein-rich food in diets when income rises. However, as meat consumption rises, additional crops are cultivated for livestock feed. Food production grows faster than livestock and crop production since the value of food includes higher shares of costs with other non-agricultural inputs and value-added components (payments to capital and labor).

Trends in agriculture and food sectors vary among regions of the world and reflect important emerging structural changes (Figure 21). The Developed countries face lower increases in the value of food and agricultural production, as population and economic growth, and therefore growth in demand, are lower than in other regions. Food and agricultural output grow faster in the Rest of the World region as population and income rises faster, and the value of crop production still plays a relevant role in final demand. The Other G20 region consists of countries that are less wealthy than those in the Developed region, but whose income is higher than in the Rest of the World region. The Other G20 has a larger population than other regions by 2050, and its GDP will exceed that of the Rest of the World, resulting in the highest values of food output by 2050.

Greater agricultural yields will prevent high increases in prices (**Figure 22**). By 2050, food

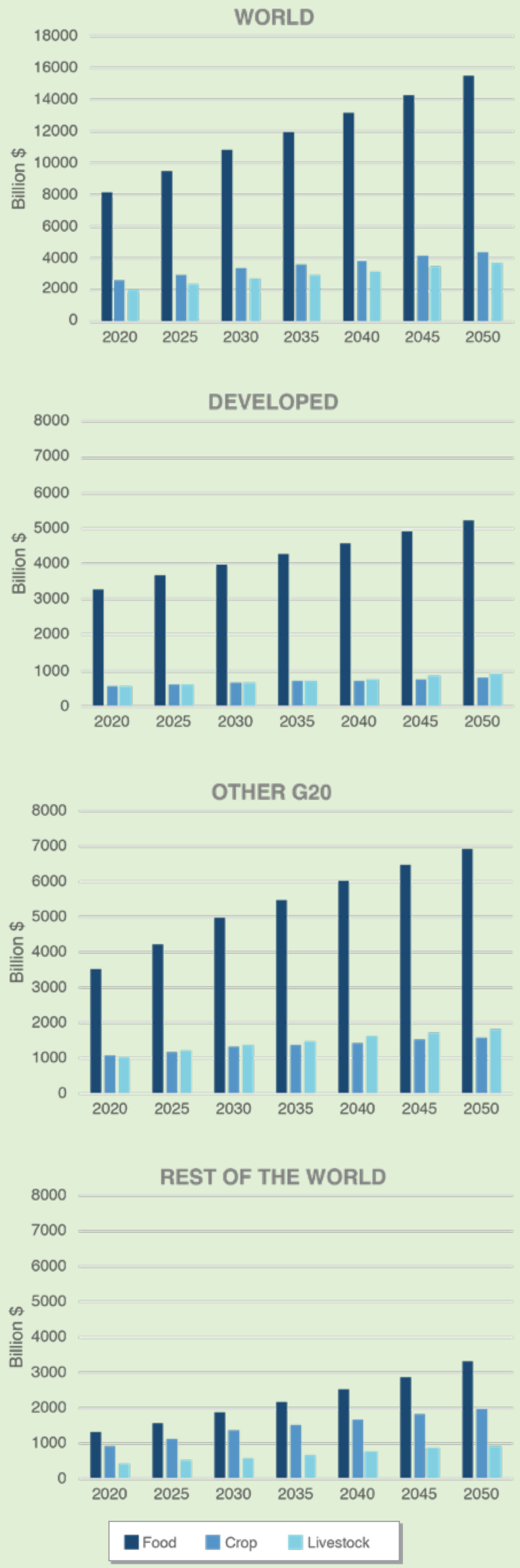

Figure 21. Food, crop and livestock production in the *Paris Forever* scenario for the World (first), Developed region (second), Other G20 region (third), and Rest of the World region (fourth)

prices are only 2% higher than in 2020. Crop prices rise a bit more (by 7%), while livestock prices rise by 42% and forest products by 33%. The stability in food prices is due to the rising importance of the value-added component in food production, while livestock prices are impacted by higher demand for meat as income rises. Land use for grazing is also an important input in livestock production, and its costs contribute to higher livestock prices. Finally, forest products are more impacted by land prices, since land is a larger input share for forest production.

Global projections for food and agriculture production and prices until 2050 under the *Paris 2°C* scenario are quite similar to those under the *Paris Forever* scenario (**Figure 23**). The value of crop output is 1.5% lower in the *Paris 2°C* scenario, while livestock output reduces by 1.9% and food output by 2.3%. Changes in prices are also quite modest, but a bit more discernable than changes in output, since food and agricultural prices are inelastic (quantities respond less to changes than prices). Prices of livestock products initially increase under the *Paris 2°C* scenario, declining later by 4% by 2050 compared to the *Paris Forever* scenario, while prices of food products and crop products decrease by 5.4% and 2.8%, respectively. These changes result from smaller growth in GDP under the *Paris 2°C* scenario by 2050. They also reflect the fact that demand for livestock and food are more elastic to prices than crops, and livestock is more intensive in GHG emissions.

Implications

Agriculture and food production will keep growing until mid-century, mostly due to income growth in the Other G20 and Rest of the World regions. This will increase pressure for land-use change, water use, and use of energy-intensive inputs, which will also lead to higher GHG emissions. The *Paris 2°C* scenario has low impacts on agriculture and food production trends by mid-century since its effects on economic growth are mild by that time. Livestock production is slightly more impacted than crops, since it is more intensive in GHG emissions. Although economic growth tends to shift demand toward more protein-rich food sources, higher carbon costs associated with livestock production drives demand downward, decreasing its prices, and such impacts are transmitted to the food sector.

More Information

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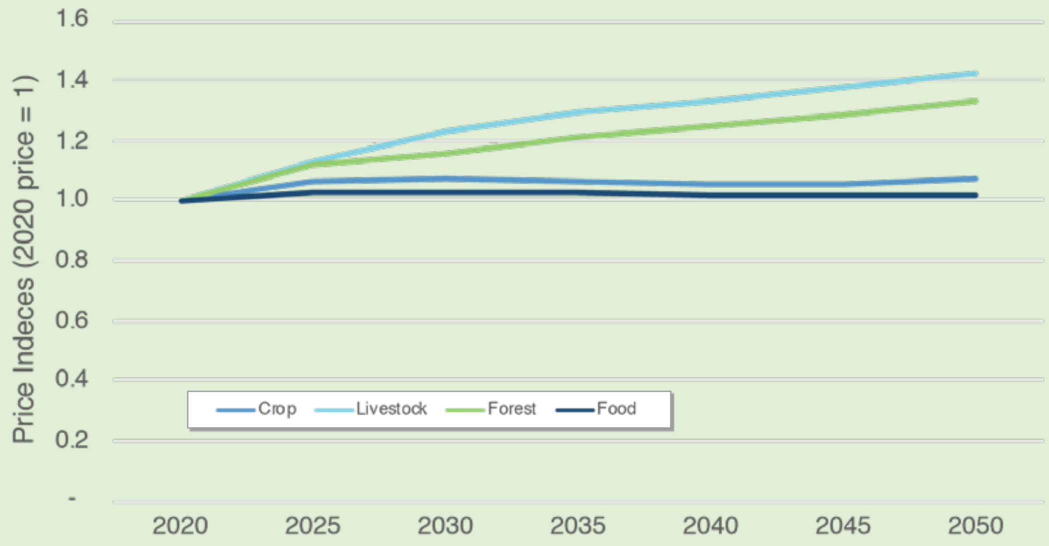

Figure 22. Global price indices for crop product, livestock product, forest product and food product in the *Paris Forever* scenario

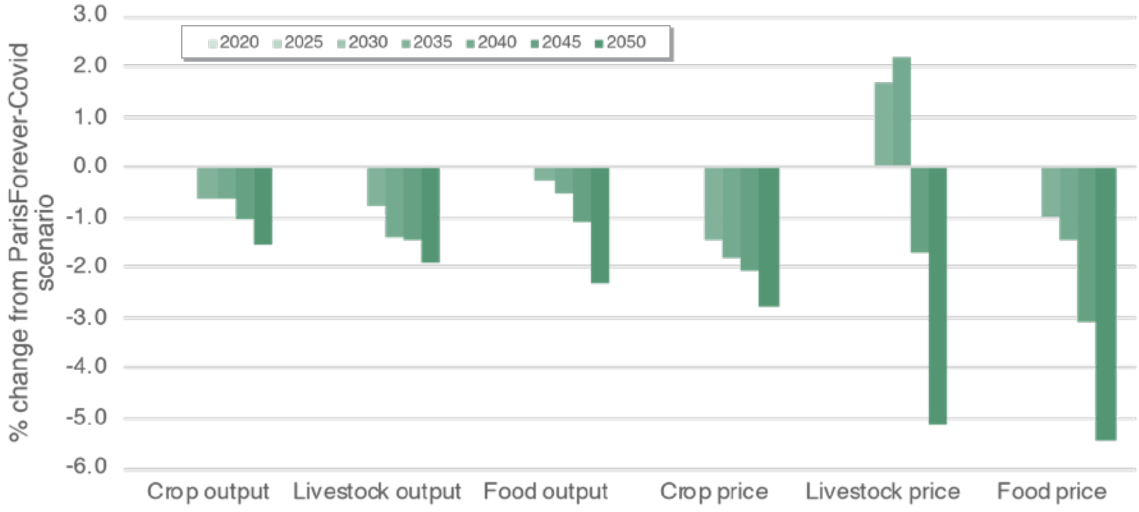

Figure 23. Changes in output and prices of crop, livestock and food in the *Paris 2°C* scenario relative to the *Paris Forever* scenario

Land-Use Change

Context

Larger agricultural and food production requires more natural resources such as land and water. However, continued yield improvements could serve to limit expansion of agricultural areas.

Key Findings

Global land-use projections from 2020 to 2050 are quite stable under the *Paris Forever* scenario (**Figure 24**). Natural forest areas decrease by 1% and natural grasslands by 3% over that period. These are converted mostly to cropland areas, which increase by 7%, while pasture lands increase by only 0.14%. These changes are much lower than increases in agricultural and food production due to a continuous increase in yields driven by technological change and changing agricultural management practices. In the case of pasture areas, there is a gradual intensification process leading to higher productivity in livestock production, with an increasing use of capital, inputs and management reducing the area needed for each unit of output. Acreage dedicated to biomass for energy increases by 38%, but as it occupies only 2.9% of the total cropland area in 2020, it remains relatively small in 2050 (3.7% of the total cropland area).

By 2100, population growth slows down and income elasticities of food demand (changes in food demand due to changes in income) decline with rising income. As a consequence, cropland area is only 2.3% larger than in 2020, while pastureland is 0.44% larger. Natural forests and natural grasslands decrease by 2% and 4% by 2100, respectively. Biomass area increases by 126% compared to the 2020 area to cope with the growth of bioenergy output, but the total biomass area covers only 6% of total cropland.

Cropland areas in the Developed region are 3% larger in 2050, but decrease by 1% in 2100, while pasture area does not change by 2050, but increases by 2% by 2100. These results reflect gains in yields, an absence of population growth in developed countries, and higher global demand for protein sources, some of which is met by exports from the Developed region. The natural grass area decreases by 1% by 2050 and 2100, due to conversion to pasture areas, while natural forests increase by 2%.

Cropland in the Other G20 region increases by 2% in 2050, but decreases by 3% by 2100. Livestock intensification leads to decreasing pasture areas by 1% in 2050 and by 2% in

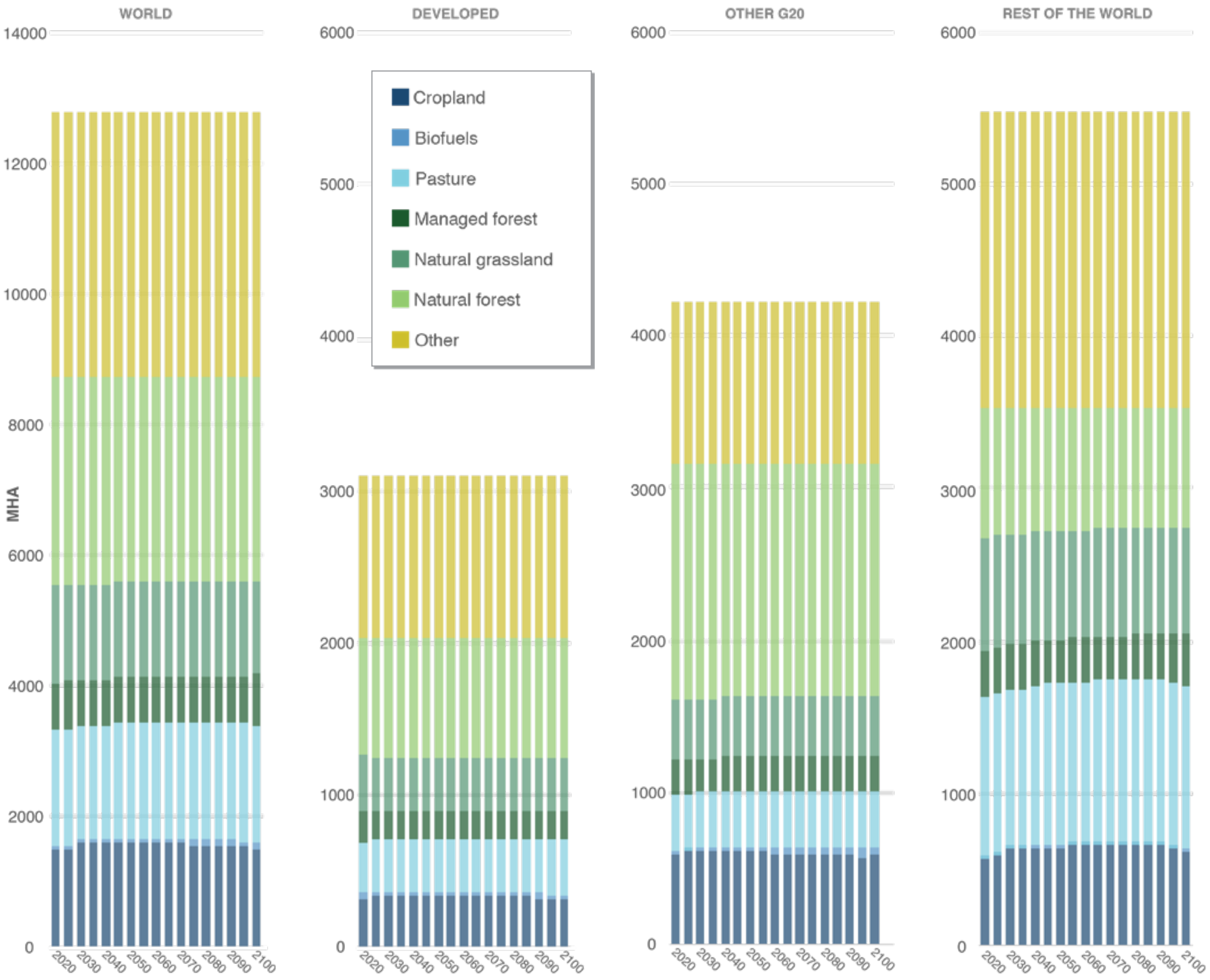

Figure 24. Land use in the *Paris Forever* scenario at the global level (far left), in the Developed region (center left), in the Other G20 region (center right), and in the Rest of the World region (far right)

2100, providing a runway for the expansion of cropland and bioenergy. Natural grass areas decrease by 3% in 2050 and by 5% in 2100, while natural forest areas decrease by 0.4% and 0.5%, respectively. Land for bioenergy covers 4% of the total cropland area by 2050 and 10% by 2100.

The Rest of the World region faces larger land-use changes than other regions due to larger increases in population and income. The cropland area increases by 14% by 2050 and by 10% by 2100. Pasture area grows by 1% by 2050 and 2100. The expansion of agricultural areas leads to more conversion of natural ecosystems. Natural grasslands decrease by 4% by 2050 and 6% by 2100, while natural forests reduce by 5% and 8%, respectively. Land for bioenergy production undergoes major increases (222% by 2050 and 719% by 2100), however, as land dedicated to bioenergy in 2020 is so small, bioenergy reaches only 0.6% of total cropland area by 2050 and 1.5% by 2100.

Land-use changes in the *Paris 2°C* scenario are similar to those in the *Paris Forever* scenario by 2050, but quite different by 2100 (**Figure 25**). By 2100, the area dedicated to bioenergy output in the *Paris 2°C* scenario reaches 17% of total cropland area, while it is only 6% in the *Paris Forever* scenario. Cropland area also increases by 22%, while pastureland decreases by 31% to give room for cropland and bioenergy expansion. As livestock production is more GHG emissions-intensive than crop production, the strong effort to reduce emissions at the end of the century in the *Paris 2°C* scenario induces greater livestock intensification, with larger use of crops as feedstock and lower animal production cycles, since emissions per unit of output are lower in more efficient production systems.

Implications

Productivity and yield gains contribute to modest expansion of agricultural areas throughout the century. The increased use of land for crops and bioenergy in the *Paris 2°C* scenario induces more deforestation than in the *Paris Forever* scenario by 2100, primarily in the Other G20 region, although in both scenarios, total natural forest loss remains low (2.2%), as does loss of natural grassland areas. Crop-yield gains and intensification in livestock production under GHG emissions constraints are key to containing unintended consequences from large biomass production, such as larger conversions of natural ecosystems and associated emissions.

More Information

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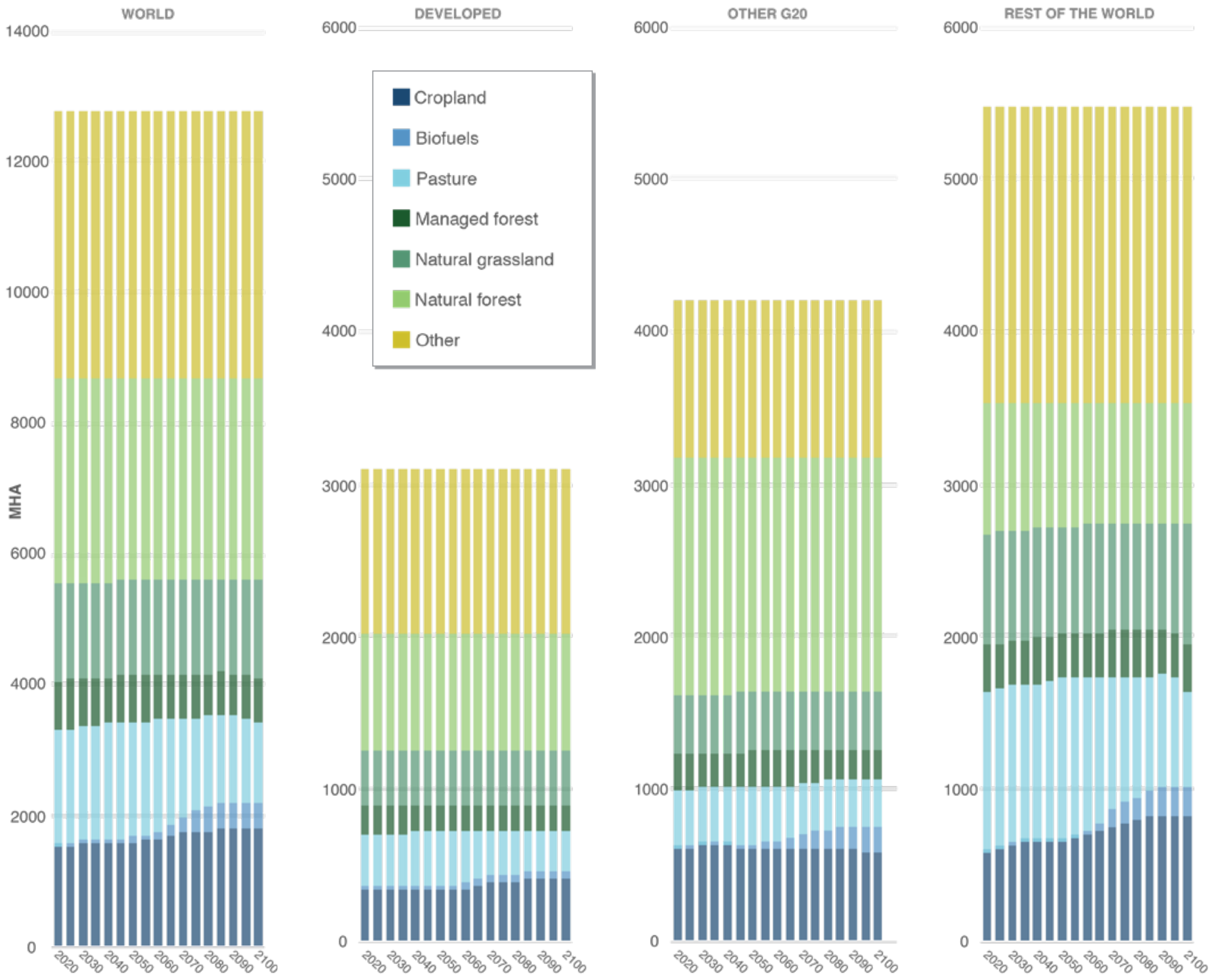

Figure 25. Land use in the *Paris 2°C* scenario at the global level (far left), in the Developed region (center left), in the Other G20 region (center right), and in the Rest of the World region (far right)

Climate

GHG Emissions by Gas/ Source and Region

Context

Anthropogenic greenhouse gas (GHG) emissions result from a wide range of industrial, agricultural and consumption activities. 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

Our projections show that societal responses to Covid-19 reduced global fossil CO_2 emissions by 4% in 2020. Relative impacts on total GHG emissions are smaller, with about a 3% reduction, because other GHG emissions decline slightly less in percentage terms than those from fossil CO_2. We project that Covid-19 impacts on global GHG emissions persist but diminish over time—a 2% reduction by 2025 and about 1% in 2030–2040 below what they would be in a non-Covid world. After that, the difference imposed by the pandemic is less than 1%.

We project that global GHG emissions in the *Paris Forever* scenario initially decrease from about 48 gigatonnes of CO_2-equivalent (Gt CO_2e) in 2020 to about 47.5 Gt CO_2e in 2030, and then gradually increase to about 51 Gt CO_2e in 2050 (**Figure 26**) due to growth in countries with less stringent emissions targets. While GHG emissions in the Developed regional grouping are lower by 23% in 2050 relative to 2020, this reduction is counterbalanced by an increase in GHG emissions in the Other G20 and the Rest of the World, where emissions during that period grow by 8% and 35%, respectively.

In the *Paris 2°C* scenario, GHG emissions follow the same path as in *Paris Forever* until 2030, and then more aggressive policies reduce emissions to 34 Gt CO_2e by 2050 (**Figure 27**). In this scenario, emissions in the Developed region decrease by 47% from 2020 to 2050, with corresponding reductions in the Other G20 and Rest of the World of 24% and 17%.

In the *Accelerated Actions* scenario (**Figure 28**), global GHG emissions are projected to decline to 20 Gt CO_2e by 2050. Globally, the world reduces its GHG emissions by almost 60% in 2050 relative to 2020. In this period, emissions in the Developed regional grouping, Other G20 region and the Rest of the World decline by 77%, 60% and 33%, respectively. Ambitious changes in current policy approaches will be needed to achieve emissions reductions of this magnitude.

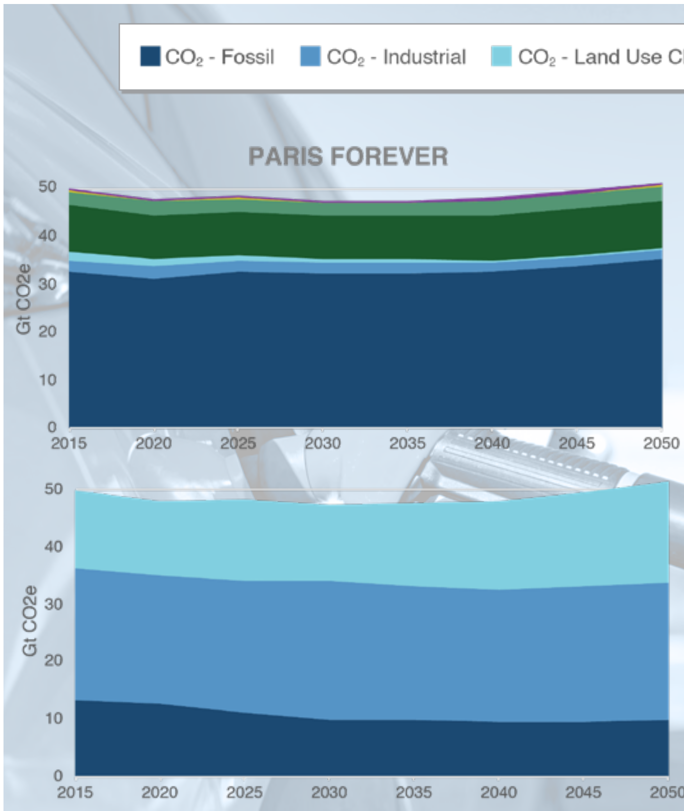

Figure 26. Global annual GHG emissions in the *Paris Forever* scenario by gas (top) and regional group (bottom)

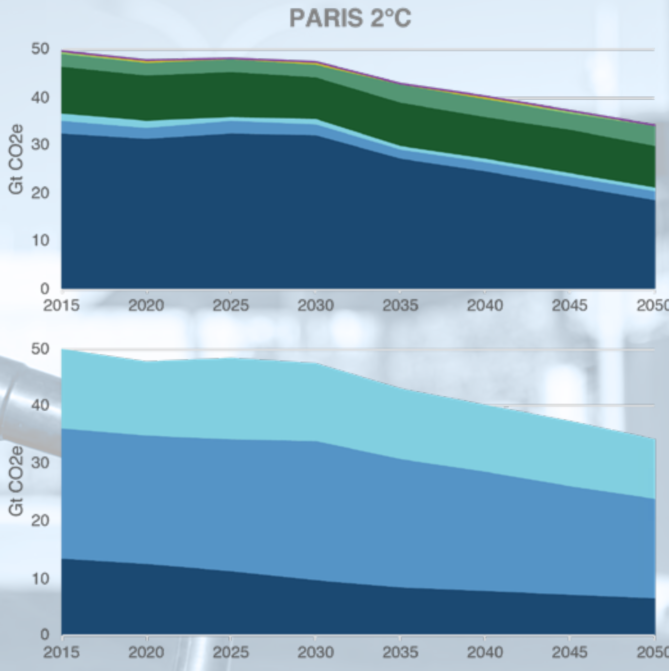

Figure 27. Global annual GHG emissions in the *Paris2°C* scenario by gas (top) and regional group (bottom)

We also extend our projections to 2150 (**Figure 29**) based on the scenario descriptions provided in Table 2. Global GHG emissions in the *Paris Forever* scenario continue their gradual increase after 2050 due to global population and GDP growth. Global emissions in the *Paris 2°C* scenario decline to about 10 Gt CO_2e by 2100 and then remain at that level. Two scenarios that stabilize global average surface temperature at 1.5°C relative to pre-industrial levels differ by the initial emissions reduction trajectory. In one scenario (*Paris 1.5C*), emissions decrease sharply after 2025; in the other scenario (*Accelerated Actions 1.5C*), they decrease more gradually starting in 2020. We also test the case where emissions decrease gradually starting in 2020, dropping to almost zero by 2070 and staying at that level thereafter (*Accelerated Actions (NZE2070)*). These scenarios of aggressive actions illustrate 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 after 2030. Overall, projected emissions in the *Paris Forever* scenario show trends similar to our previous Outlooks with some decrease (in 2100, emissions total 64 Gt CO_2e vs. 69 Gt CO_2e in the 2018 Outlook) due to updated projections for GDP and population growth in the 21st century. Covid-19 is projected to have a short-term direct impact on greenhouse gas emissions. The longer-term effect will be most pronounced if the pandemic acts as a catalyst for accelerated emissions reduction. Ultimately, robust government policies will be needed for aggressive GHG emissions mitigation.

More Information

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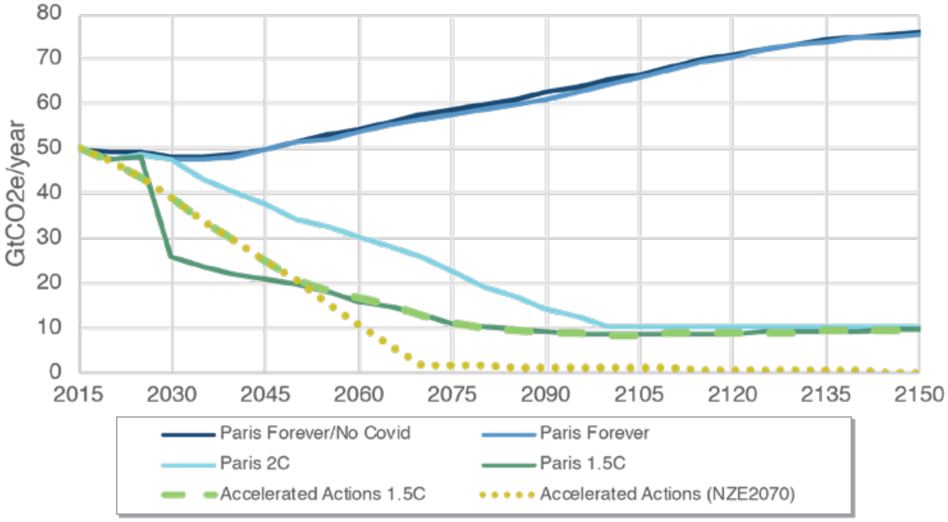

Figure 29. Global annual GHG emissions up to 2150

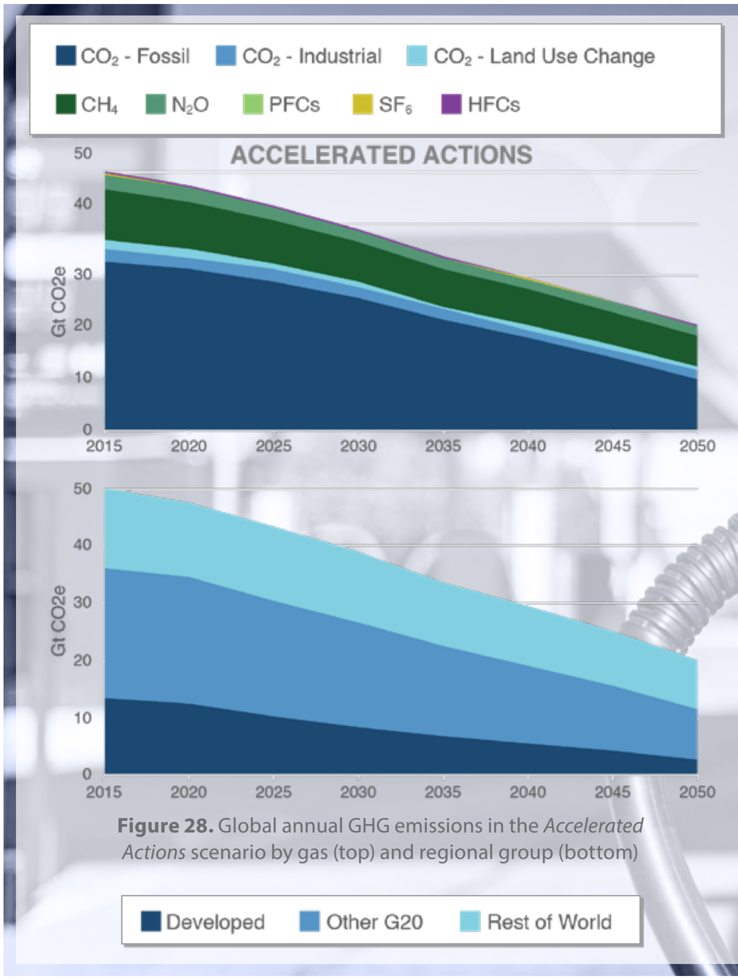

Figure 28. Global annual GHG emissions in the *Accelerated Actions* scenario by gas (top) and regional group (bottom)

Implications of Recent Emissions Trends and Future Projections

Context

Anthropogenic emissions boost atmospheric concentrations of radiatively-active trace gases that interfere with the Earth's energy balance. The strength of this interference is defined as radiative forcing, or the net increase of energy (or heating) contained within the global climate system. To evaluate the potential effectiveness of emissions-reduction commitments in the Paris Agreement or other climate policy instruments, we use the IGSM to model such actions and the Earth system's response in terms of trace-gas concentrations, radiative forcing and global climate trends. However, complexities within both human/socioeconomic systems and the Earth's geophysical, chemical and thermodynamical 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 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 carbon dioxide (CO_2) concentrations in the *Paris Forever* scenario will continue to rise throughout (and after) the 21st century (**Figure 30**). These trends are amplified—particularly toward the end of the 21st century and thereafter—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).

In the coming decades, an important climatic threshold is crossed by the beginning of the 2040s: the entirety of the IGSM ensemble projection rises above 450 ppm of global CO_2 concentrations. In addition, by the middle of the next century, more than half of the IGSM ensemble runs (i.e., at least 50% probability) show CO_2 concentrations at twice the most recent observed levels (**Figure 31**). From a CO_2e perspective, this doubling time is not only shortened but enhanced. By the mid-22nd century, we project with 100% likelihood that CO_2e concentrations will rise to at least double the current level. There is a greater than 50% likelihood of this doubling to occur by 2120 (i.e., 30 years prior to the CO_2-only doubling).

The trends and likelihoods in the radiative forcing of climate show similar increases to the CO_2e trends (**Figure 32**). As a point of comparison, our *Paris Forever* scenario aligns 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 attained at the end of the century. However, in the *Paris Forever* scenario there are no indications of climate-forcing stabilization (as in the RCP6.0 scenario), and in particular, there are indications of a skewed distribution of the radiative forcing by the end of the century and into the 2100s. This skewness indicates a higher likelihood of the radiative forcing to be toward the upper bound of our 90% probability range (shaded region of Figure 31). Despite this trend, we find no likelihood of exceeding a radiative forcing greater than 8.5 W/m^2 by mid-22nd century. Therefore, the IPCC's RCP8.5 outcome (8.5 W/m^2 radiative forcing) is seen as an extreme, if not improbable, pathway under our *Paris Forever* projections.

Nevertheless, the increases in human-caused radiative forcing under the *Paris Forever* scenario lead to salient and unimpeded trends in the global climate response (**Figure 33**). Consequently, important climate thresholds are crossed in the coming decades, and given our probabilistic approach, we can provide a risk-based perspective. One of the most recognized climate targets is to remain below a global climate warming of 2°C (from pre-industrial conditions). We find that by 2065, more than half of the IGSM ensemble projections for *Paris Forever* exceed 2°C global climate warming, a fraction that rises to more than 75% by 2071 and more than 95% by 2085. By 2100, 95% of the IGSM projections indicate a global climate warming of at least 2.25°C, and the central tendency (i.e., median) of the projected warming is 2.8°C. With respect to the Paris Agreement's most

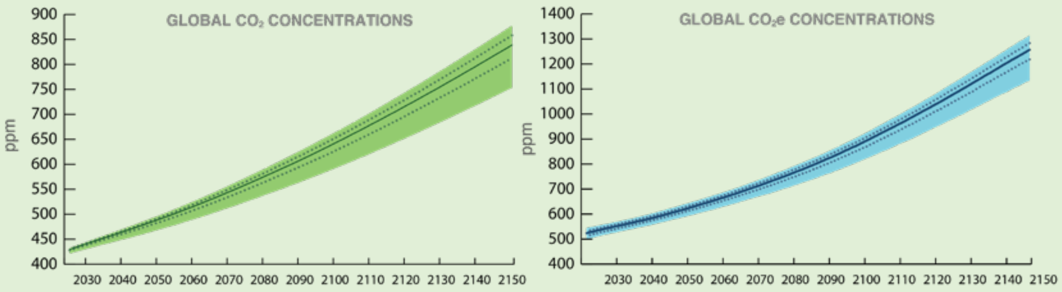

Figure 30. Global atmospheric concentrations of carbon dioxide (left) and equivalent carbon dioxide (right), based on the *Paris Forever* ensemble scenario. The solid line represents the median result of the IGSM ensemble, the dashed lines denote the interquartile (25th to 75th percentile) range, and the shaded region depicts the 5th to 95th percentile range of values. Units are in parts per million (ppm).

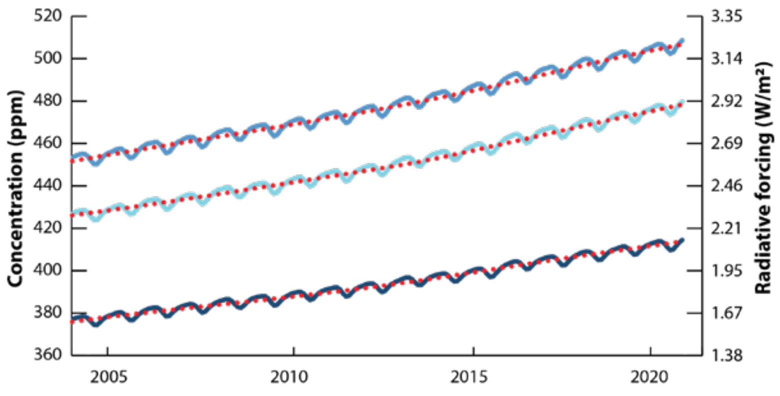

Figure 31. Concentrations (ppm) and corresponding radiative forcing (W/m^2) of CO_2 and equivalent CO_2 (CO_2e) following the approach described in Huang *et al.* (2009). The non-CO_2 gas concentrations are measured in the AGAGE network (Prinn *et al.*, 2018) and the CO_2 concentrations are from the NOAA Monitoring Division (NOAA, 2018). The CO_2e values 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.

aggressive climate target of not exceeding 1.5°C warming, the *Paris Forever* ensemble scenario is very unlikely to meet this target much beyond mid-century—with all of the ensemble's warming projections exceeding 1.5°C warming after 2055. By the mid-22nd century, the IGSM projections show that the world experiences at least 3.3°C of warming (in 95% of the IGSM ensemble runs) and most likely a warming of 4.1°C (median result).

Globally speaking, a warming climate enhances the energetics of the atmosphere, thereby accelerating the global hydrologic cycle (i.e., increasing global evaporation and precipitation). Thus the scientific community uses the term "hydrologic sensitivity" to characterize the (relative) precipitation response to human-forced global warming. From the IGSM's large ensemble of projected global precipitation rates (bottom panel, Figure 33) and corresponding temperature, we find the MIT Earth System Model's (MESM's) global hydrologic sensitivity ranges from 1.7–3.3% per °C. This range is slightly larger than that from the most recent estimates across (a smaller ensemble of) climate models from the IPCC Coupled Model Intercomparison Project (CMIP), found to be 2.1–3.3% per °C.

Given this range in hydrologic sensitivity, the MESM's projected increase in global precipitation between present day to mid-century is most likely (i.e., median result) to be 0.04 mm/day. To put that number in more practical terms, that amounts to 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). But, as discussed in a previous section, this does not alleviate water stress and shortages faced by much of the world's population. This does, however, raise the risk of extreme precipitation events as well as the frequency and severity of flooding. By the end of the century, the total change in precipitation relative to present day will likely rise to at least 0.11 mm/day (or 21,200 km^3/yr—nearly triple that of the mid-century change).

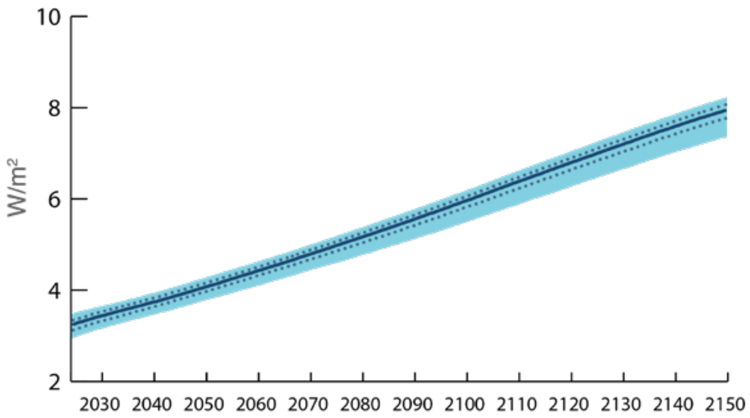

Figure 32 Total radiative forcing (units of W/m^2) that result from the EPPA emissions of radiatively-active gases, based on the *Paris Forever* ensemble scenario. Values are calculated relative to 1861–1880. the solid line represents the median result of the IGSM ensemble, the dashed lines denote the interquartile range, and the shaded region depicts the 5th to 95th percentile range of values.

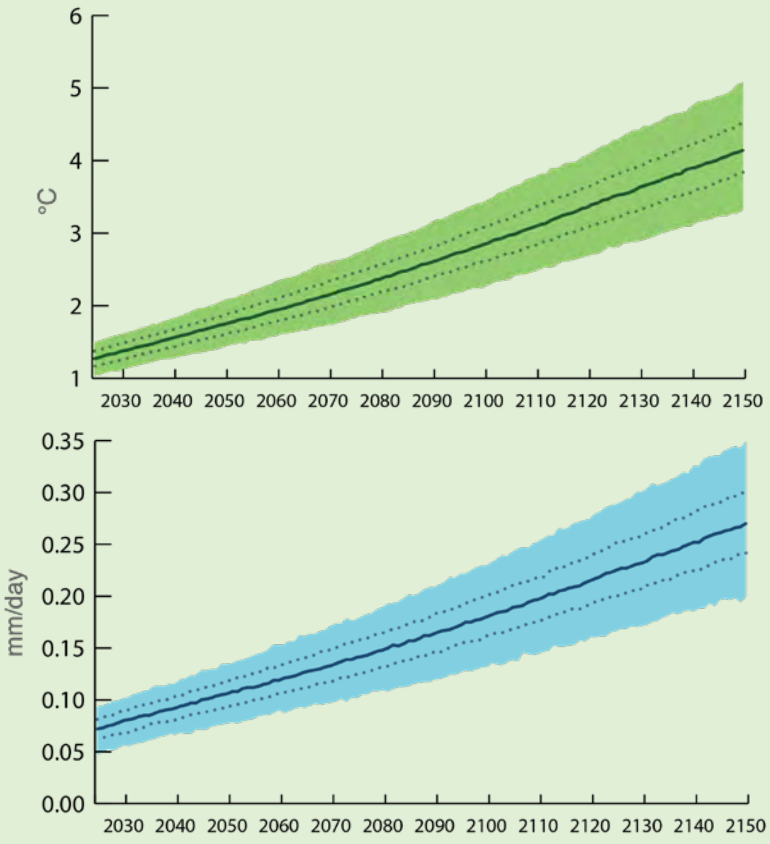

Figure 33. Annual changes in global mean surface-air temperature (top panel, in units of °C) and precipitation rate (bottom panel, in units of mm/day), based on the *Paris Forever* ensemble scenario. Changes are calculated from the 1861–1880 mean. In each panel of results, the solid line represents the 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.

Implications

The projected global climate responses under the *Paris Forever* scenario indicate with near certainty that the world will surpass critical trace-gas concentration thresholds and climate targets in the coming decades. While this scenario provides no mechanism to stabilize human-forced climate change through the mid-22nd century, it does avert the most extreme IPCC projection (RCP8.5) of human-forced climate change. While *Paris Forever* represents an unprecedented international commitment to combat climate change, more action is needed. We identify the climate benefits and risk abatement from more aggressive mitigation actions in the sections that follow.

More Information

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Beyond "Co-Benefits": A New Framework for Assessing Sustainability

Noelle Selin, Associate Professor, MIT Institute for Data, Systems and Society and MIT Department of Earth, Atmospheric and Planetary Sciences

Addressing climate change is vitally important to protect human health, but scientific and policy dialogue on climate mitigation focuses largely on meeting temperature targets. Would the design and implementation of climate policy be different if it explicitly prioritized people's health and well-being?

The Covid-19 pandemic, which impacted billions of lives across the globe in 2020, underscores the primacy of health as a major constituent of human well-being. It is no surprise that individuals—especially in the midst of a pandemic—place a high value on the health of themselves and their loved ones, and that people vulnerable to the impacts of disease prioritize preventive measures and support the development and widespread use of life-saving vaccines. The Covid-19 experience also shows that the economic well-being of communities and nations relies on a healthy, productive work force.

Research increasingly acknowledges that the well-being of people around the world is deeply connected to the health of the planet, a realization reflected in the emerging field of planetary health. A major factor in this connection is climate change, which links to human health in several ways.

First, warming temperatures cause heat-related illnesses and deaths; high levels of warming could lead to temperatures so extreme that they could exceed the limits of human survivability (Pal *et al.*, 2016). Second, climate change, including the extreme weather events that it amplifies, can alter the distribution of and human exposure to environmental pollutants. People's exposures to waterborne disease are expected to increase, and climatic factors affect the distribution and prevalence of vector-borne diseases such as those carried by mosquitoes and ticks. Finally, mental health concerns have also been linked to climate change. Some individuals and groups will experience disproportionate consequences to their health from climate change, such as increased exposures to diseases and pollutants—and among the most vulnerable populations are people with low incomes, communities of color, children and older adults.

A large body of research has shown that actions to mitigate climate change—in particular, reducing reliance on fossil fuels—can also have other substantial, near-term benefits, often in the form of reduced air pollution. Scientists and policymakers have often referred to improvements in air quality resulting from climate action, and their associated reductions in mortalities and health burdens, as "co-benefits." But if the present and future well-being of all people is the priority, this term seems at odds with the underlying reason for taking action in the first place. To reflect these priorities, researchers and policymakers should retire the concept of "co-benefits." This could change the way they inform and design policies that benefit health in the near and long term—and for which climate action is a necessary ingredient.

The Promise and Perils of "Co-Benefits"

In order to move beyond the term "co-benefits," we must first understand how climate change and health-damaging air pollutants are fundamentally connected.

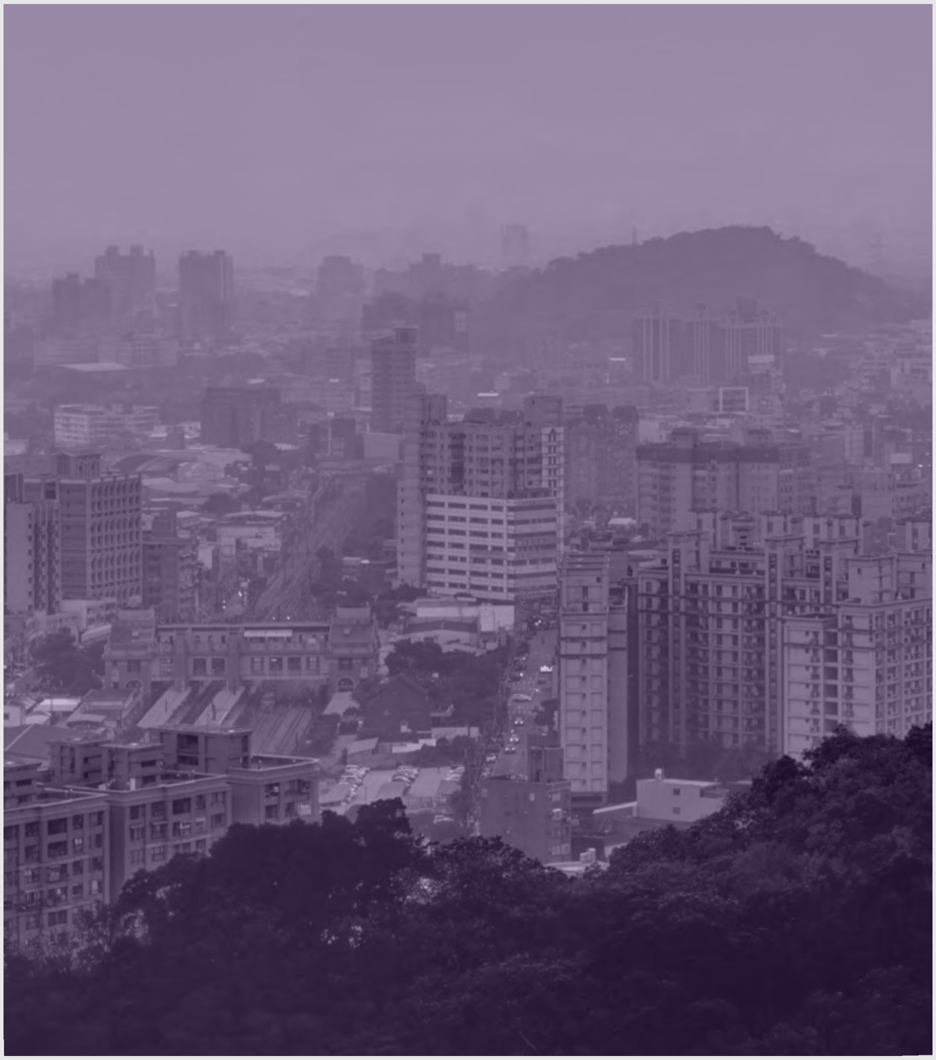
Fossil fuel combustion that leads to carbon emissions also leads to air pollution, including higher concentrations of $PM_{2.5}$ (fine particulate matter ≤ 2.5 microns in size) and ozone (O_3). These pollutants cause severe damage to cardiovascular and respiratory systems. Air pollution results in millions of premature deaths worldwide annually, and also has many more non-fatal health impacts that hamper quality of life and productivity (e.g. as seen in the 2020 wildfires in the western United States). Further, as the climate warms, the chemical reactions that produce $PM_{2.5}$ and O_3 can be enhanced, and changes in weather patterns can alter the ways in which these pollutants are transported through the air. This can lead to increased concentrations of pollutants in some already-polluted regions, even if overall emission levels stay the same (Fiore *et al.*, 2015). Mercury is another pollutant emitted from fossil fuel burning, and its distribution and cycling is increasingly affected by climate change (Obrist *et al.*, 2018).

The connection between climate change and health-damaging air pollution means that efforts to reduce the burning of fossil fuels can have substantial benefits for human health. Fossil fuel use leads to an estimated 3.6 million global premature deaths (Lelieveld *et al.*, 2019) annually, but accelerated carbon reductions in the next 80 years to meet a 1.5°C (instead of a 2°C) target could prevent more than 150 million premature deaths worldwide in that period (Shindell *et al.*, 2018). China's efforts to achieve its initial commitment under the Paris Agreement could result in nearly 100,000 avoided premature deaths in 2030, which, when monetized using common methods, could partially or fully offset policy costs (Li *et al.*, 2018). Similar results have been shown in the U.S., where policies such as carbon pricing or clean energy standards result in air pollution benefits that more than offset the policy costs

(Thompson *et al.*, 2014). This is also the case at regional and state levels for clean energy policies (Dimanchev *et al.*, 2019).

It is thus clear that policies that reduce fossil fuel use can both mitigate climate change and result in large benefits for air quality. However, these "win-win" scenarios are not a given. Some efforts to reduce greenhouse gases can actually increase air pollution. For example, recent illegal efforts by automobile companies such as Volkswagen to reduce fuel consumption for diesel vehicles resulted in degraded air quality (Chossière *et al.*, 2017). Relying on climate policy may also be an inefficient way to benefit health in the absence of other measures. Recent work shows that climate mitigation efforts alone could reduce mercury emissions in China (because of reduced coal use), but pollution control policies resulted in even greater cuts (Mulvaney *et al.*, 2020) such as those of the Minamata Convention on Mercury. In that work, we assess how mercury emissions and deposition reductions from national climate policy in China under the Paris Agreement could contribute to the country's commitments under the Minamata Convention. We examine emissions under climate policy scenarios developed using a computable general equilibrium model of China's economy, end-of-pipe control scenarios that meet China's commitments under the Minamata Convention, and these policies in combination, and evaluate deposition using a global atmospheric transport model. We find climate policy in China can provide mercury benefits when implemented with the Minamata policy, achieving in the year 2030 approximately a 5% additional reduction in mercury emissions and deposition in China when climate policy achieves a 5% reduction per year in carbon intensity (CO_2 emissions of 9.7 Gt in 2030).

In addition, climate policies may not be implemented fast enough to deliver health benefits to the most vulnerable. Delays in implementing air pollution policies, for example, have been shown to disproportionately harm low-income populations (Saari *et al.*, 2017). In that work, we find that mortality incidence rates decrease with increasing income. Modeled ozone levels yield a median of 11 deaths per 100,000 people in 2005. Proposed policy reduces these rates by 13%. Ozone reductions are highest among low-income households, which increases their relative welfare gains by up to 4% and decreases them for the rich by up to 8%. The median value of reductions in 2015 is $30 billion (in 2006 U.S. dollars).



From "Co-Benefits" to a Systems Approach

The goal of ensuring that the average global temperature increase above the pre-industrial level stays within a 2 or 1.5°C target will do much to mitigate the effects of climate change on human health in the longer term. However, such temperature targets are necessary, but not sufficient, conditions to enhance human well-being in the present and future.

Climate mitigation policy is best viewed as a means to address the broader challenges of sustainability. In that context, the term "co-benefits" may well have outlived its usefulness. "Co-benefits" in regulatory use refers specifically to benefits that are not the direct purpose of a regulation or policy. However, addressing air pollution is not secondary to addressing climate change: solving both at the same time is integral to human well-being. Climate action is also a critical prerequisite to ensuring food security, expanding access to clean water and sanitation, and protecting a wide range of ecosystem services.

Assessing climate change and air pollution in the larger context of sustainability is complex. New frameworks and approaches are needed that can address the systemic implications of policies, physical and societal interactions, and the potential for interventions to move societies towards sustainability. One example of such an approach is the new human-technical-environmental (HTE) systems framework and its related matrix-based approach that was recently applied to assess mercury pollution in the context of sustainability transitions (Selin & Selin, 2020). Further, while the 2°C target is a critical and important metric, other measures that specifically relate to human health are also needed to focus attention on outcomes that impact human well-being. Those designing and implementing policies to mitigate climate change should not just calculate their "co-benefits," but instead craft comprehensive solutions to promote human health and well-being in multiple dimensions.

Climate Risk: Physical Risk

Context

To identify climate-related risks across natural, managed and built environments, we must describe the distributions of possible future climate outcomes across a wide range of spatial and temporal scales that reflect national interests, global and regional resource networks, infrastructure, operational assets and other key considerations. Constructed with our Integrated Global System Modeling (IGSM) framework, the Outlook 2021 scenarios are designed to provide an objective sampling of the plausible responses and outcomes that result from a global policy or environmental target. 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 which combines the global-scale distribution of human-forced climate change with the more spatially-resolved climate-response patterns. Our recently updated downscaling procedure incorporates the latest climate-model information from the Coupled Model Intercomparison Project Phase 6 (CMIP6), improving spatial details and nearly doubling the size of our ensemble of climate outcomes. The result is a more inclusive representation of climate-related physical risk.

Key Findings

A comprehensive assessment of all associated physical risks, worldwide, is beyond the scope of this report. Rather, we provide regional, representative features of our climate outputs to convey the broad aspects of physical risk. We focus on the results for surface-air temperature and precipitation, which relate to the frequency and intensity of several high-impact climate- and weather-related events, including heat waves, flooding and drought.

A standout finding of this analysis is that under implementation of the Paris Agreement's current (national pledges fulfilled/maintained in perpetuity) and long-term (global warming well below 2°C) climate targets, most major continents will have passed 1.5°C of warming by mid-century, even when considering the lowest 5th percentile of our ensemble results (**Figure 34** and **Table 6**). The only exceptions are Oceania and South America, where the lowest 25th percentile remains below 1.5°C.

More precisely, in a *Paris Forever* world, there is at least a 75% chance that across all continents, human-induced warming will exceed 1.5°C by 2050—and a 95% chance North America and Asia will experience warming greater than 2°C. Even in the *Paris 2°C* scenario, many of the world's continents carry a low probability (at most 25%) of staying below 2°C. South America and Oceania have a higher probability, but it's still below 50%. These results indicate that in order for the global 2°C target to be met, most of the buffered warming (i.e., less than 2°C) must occur over the world's oceans. This result is consistent with the well-known "colder-ocean warmer-land" (COWL) pattern in CMIP6 model behavior (**Figure 35**). Extending these simulations out to 2150, we find that the majority of these features are maintained (Table 6), with small weakening in the warming (i.e., of at most 0.1°C) after 2100.

Unlike the "COWL" temperature pattern response (Figure 35), precipitation changes induced by human-induced climate warming do not exhibit worldwide characteristic patterns. Therefore, we find a greater disparity in the outcomes of change across the major continental regions (**Table 7**). In addition, the seasonal aspects of precipitation change are an important factor (**Figure 36**), in which the majority of the distribution of precipitation change might switch signs from season-to-season. For example, under the *Paris Forever* scenario, Europe experiences a wetter-winter/drier-summer risk that evolves through the latter half of the century; North America shows a similar but less pronounced pattern. This underscores an underlying threat of more flood-prone conditions during the colder seasons, and, with less precipitation during the summer coupled with warmer temperatures, a compounding risk of enhanced heat-stressed and drought-prone pre-

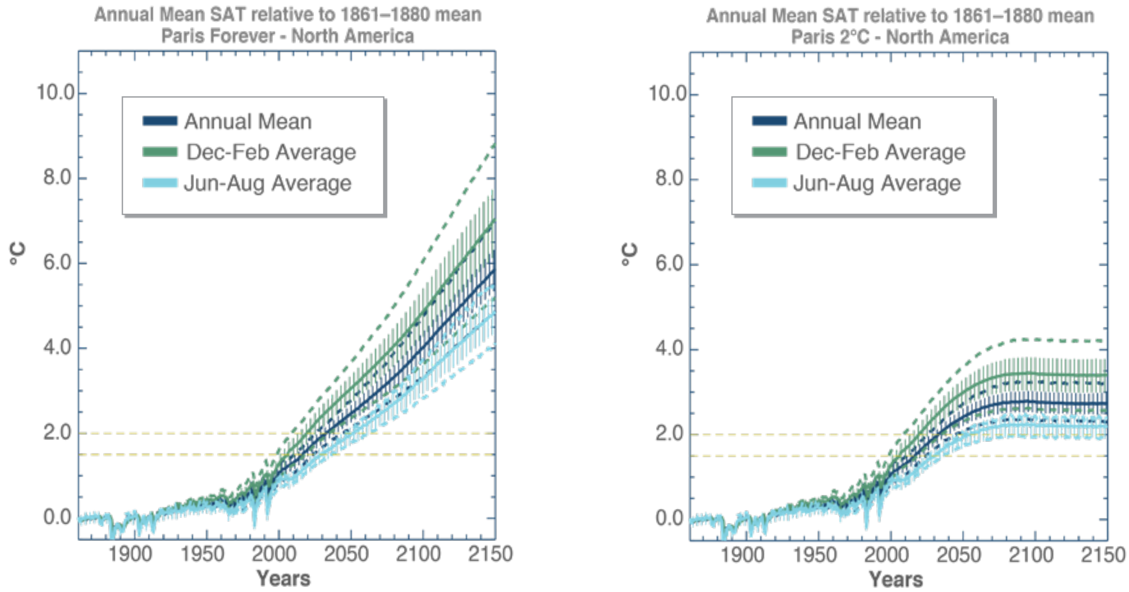


Figure 34. Projections from the *Paris Forever* (left) and the *Paris 2°C* (right) ensemble scenarios—showing the range of outcomes in surface-air temperature change (°C) averaged over North America. Our hybrid, meta-ensemble construction combines the IGSM global projections with the spatial response patterns of climate change from the latest IPCC climate model simulations. This produces an ensemble of 11,200 possible outcomes—and for each of these we determine a timeseries of the spatially averaged temperature change. The solid lines represent the median results, and the dashed lines indicate the 5th and 95th percentile. The thin (colored) bars also provide the interquartile range (25th and 75th percentile) around the median result. These results are provided for the annual mean (dark blue lines), December-February average (green lines) and June-August average (light blue lines).

vailing conditions. Based on the distribution of outcomes (Table 7), we find that these conditions have a marginal likelihood of occurring. While the central tendency aligns with this finding, the probability does not exceed 75% (i.e., in Table 7, the summer precipitation change for Europe is not negative at the 75th percentile). Under the *Paris 2°C* scenario, however, the marginal risk of these conditions to occur in summer is eliminated. However, there remains an elevated risk of increased precipitation during the winter.

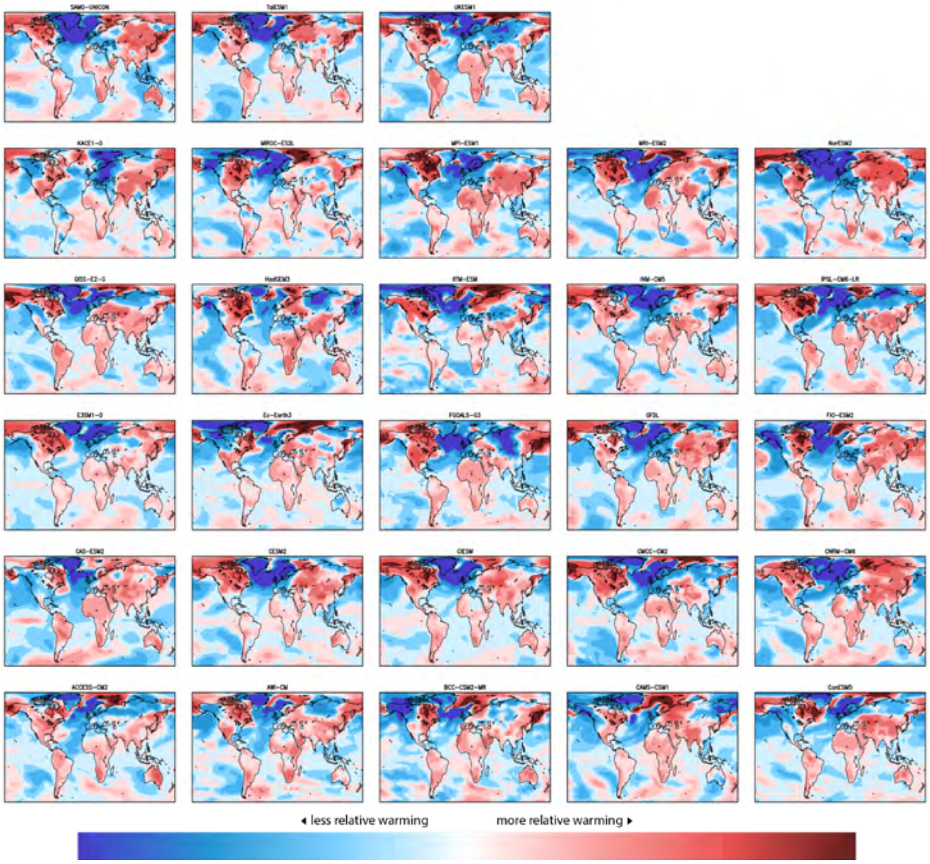


Figure 35. Illustrative maps indicating the *relative change* in surface-air temperature associated with a unit change (i.e., 1°C) in human-induced global warming. The results are displayed for all climate models participating in the Coupled Model Intercomparison Project Phase 6 (CMIP6) and that also form the basis of our "hybrid" downscaling of the IGSM global scenarios. Shades of red indicate areas where the warming is greater than the concurrent global warming; shades of blue indicate where the warming is less than the concurrent global warming. The darker shades indicate regions where this relative change is stronger.

Implications

Regardless of the success of international efforts to achieve the long-term goals of the Paris Agreement, our results underscore that elevated climate-related physical risks will continue to evolve by mid-century. The aggregate representations of risk presented in this summary are based on assessments of more detailed landscapes, and these could be further elucidated by time, resource systems (land, water, energy), socioeconomic sectors, demographics, health risks and systems, and/or environmental regimes. "Multi-sector" analyses that take all of these factors into consideration can bring the full spectrum of risks to bear and thus enable decision-makers to pursue a more holistic vision of sustainable development.

More Information

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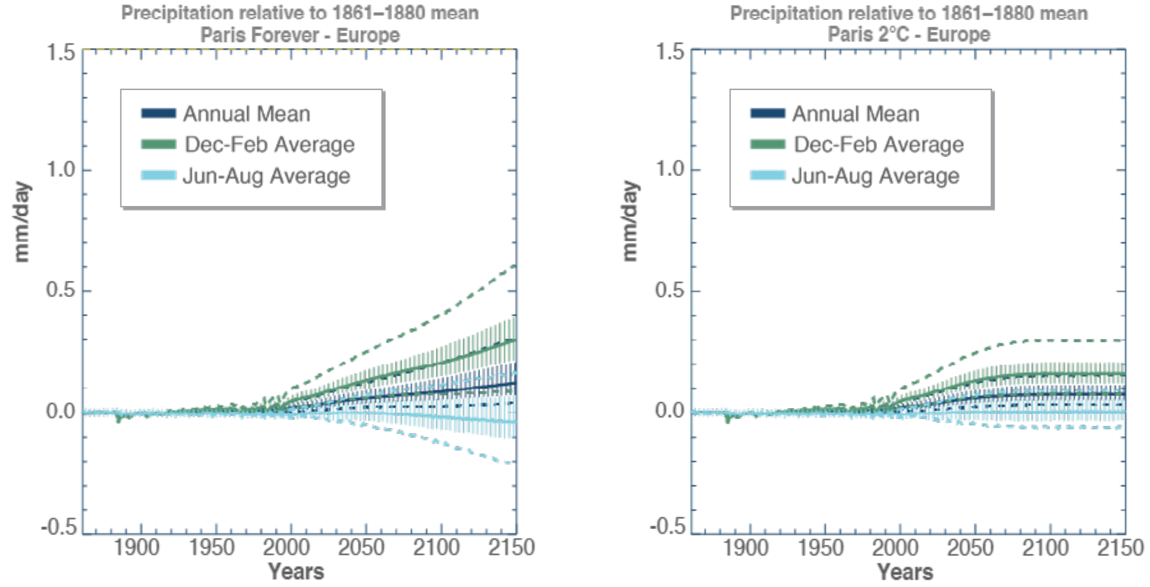

Figure 36. Projections from the *Paris Forever* (left) and *Paris 2°C* (right) ensemble scenarios—showing the range of outcomes in precipitation (mm/day) averaged over Europe. Our hybrid, meta-ensemble construction combines the IGSM global projections with the spatial response patterns of climate change from the latest IPCC climate model simulations. This produces an ensemble of 11,200 possible outcomes—and for each of these we determine a timeseries of the spatially averaged temperature change. The solid lines represent the median results, and the dashed lines indicate the 5th and 95th percentile. The thin (colored) bars also provide the interquartile range (25th and 75th percentile) around the median result. These results are provided for the annual mean (dark blue lines), December-February average (green lines) and June-August average (light blue lines).

Table 6. Summary of results from the *Paris Forever* and *Paris2C* scenarios for surface-air temperature change averaged over major continental regions. For each region, percentile values are provided for the annual, December-February (DJF) and June-August (JJA) averaged change.

			Africa					Asia					Europe				
			5th	25th	median	75th	90th	5th	25th	median	75th	90th	5th	25th	median	75th	90th
Annual	Paris Forever	2050	1.6	1.9	2.0	2.2	2.4	2.0	2.1	2.3	2.5	2.6	1.7	1.8	2.1	2.4	2.5
		2075	2.1	2.4	2.6	2.9	3.1	2.5	2.7	3.0	3.2	3.4	2.1	2.4	2.7	3.0	3.3
		2100	2.6	3.0	3.3	3.6	4.0	3.1	3.5	3.8	4.1	4.4	2.6	3.0	3.4	3.9	4.4
		2125	3.1	3.7	4.0	4.4	4.9	3.9	4.3	4.7	5.0	5.5	3.3	3.7	4.2	4.8	5.4
		2150	3.7	4.4	4.8	5.2	5.8	4.6	5.1	5.5	6.0	6.5	3.8	4.4	5.0	5.6	6.4
	Paris2C	2050	1.6	1.8	2.0	2.2	2.3	2.0	2.1	2.3	2.5	2.6	1.7	1.8	2.1	2.3	2.5
		2075	1.8	2.1	2.3	2.5	2.7	2.2	2.4	2.6	2.8	2.9	1.8	2.0	2.3	2.6	2.9
		2100	1.8	2.1	2.3	2.5	2.8	2.2	2.4	2.6	2.9	3.0	1.9	2.1	2.4	2.7	2.9
		2125	1.8	2.1	2.3	2.5	2.8	2.2	2.4	2.6	2.8	3.0	1.9	2.0	2.3	2.6	2.9
		2150	1.8	2.1	2.3	2.5	2.8	2.2	2.4	2.6	2.8	3.0	1.8	2.0	2.3	2.6	2.9
			North America					Oceania					South America				
			5th	25th	median	75th	90th	5th	25th	median	75th	90th	5th	25th	median	75th	90th
	Paris Forever	2050	2.1	2.3	2.5	2.7	2.8	1.4	1.6	1.8	2.0	2.2	1.4	1.6	1.8	2.0	2.2
		2075	2.7	2.9	3.2	3.4	3.7	1.8	2.1	2.3	2.6	2.9	1.8	2.1	2.3	2.6	2.9
		2100	3.3	3.7	4.0	4.4	4.8	2.3	2.6	2.9	3.2	3.7	2.3	2.6	2.9	3.2	3.7
		2125	4.1	4.5	5.0	5.4	5.9	2.8	3.2	3.6	4.0	4.6	2.8	3.2	3.6	4.0	4.6
		2150	4.9	5.4	5.9	6.4	7.0	3.3	3.9	4.3	4.8	5.5	3.3	3.9	4.3	4.8	5.5
	Paris2C	2050	2.1	2.2	2.4	2.6	2.7	1.4	1.6	1.7	1.9	2.1	1.4	1.6	1.7	1.9	2.1
		2075	2.3	2.5	2.8	3.0	3.2	1.6	1.9	2.1	2.3	2.6	1.6	1.9	2.1	2.3	2.6
		2100	2.3	2.5	2.8	3.0	3.2	1.6	1.9	2.1	2.3	2.6	1.6	1.9	2.1	2.3	2.6
		2125	2.3	2.5	2.7	3.0	3.2	1.6	1.9	2.1	2.4	2.7	1.6	1.9	2.1	2.4	2.7
		2150	2.3	2.5	2.7	3.0	3.2	1.6	1.9	2.1	2.4	2.7	1.6	1.9	2.1	2.4	2.7

			Africa					Asia					Europe				
			5th	25th	median	75th	90th	5th	25th	median	75th	90th	5th	25th	median	75th	90th
DJF	Paris Forever	2050	1.5	1.7	1.9	2.1	2.3	2.1	2.4	2.6	2.8	3.0	1.7	2.0	2.4	2.9	3.4
		2075	1.9	2.2	2.5	2.7	3.0	2.7	3.0	3.3	3.6	4.0	2.1	2.5	3.1	3.6	4.4
		2100	2.4	2.8	3.1	3.4	3.8	3.3	3.8	4.2	4.6	5.0	2.5	3.1	3.8	4.6	5.6
		2125	2.9	3.4	3.8	4.2	4.7	4.0	4.6	5.1	5.6	6.2	3.0	3.7	4.6	5.5	6.8
		2150	3.4	4.1	4.5	5.0	5.6	4.7	5.4	6.0	6.6	7.3	3.5	4.3	5.4	6.5	8.0
	Paris2C	2050	1.5	1.7	1.9	2.1	2.2	2.1	2.3	2.6	2.8	3.0	1.6	1.9	2.4	2.8	3.4
		2075	1.7	1.9	2.1	2.4	2.6	2.3	2.6	2.9	3.1	3.4	1.8	2.2	2.7	3.2	3.8
		2100	1.7	2.0	2.2	2.4	2.7	2.4	2.7	2.9	3.2	3.5	1.8	2.2	2.7	3.3	3.9
		2125	1.7	1.9	2.2	2.4	2.7	2.4	2.6	2.9	3.2	3.5	1.8	2.2	2.7	3.2	3.9
		2150	1.7	2.0	2.2	2.4	2.7	2.3	2.6	2.9	3.2	3.5	1.8	2.2	2.7	3.2	3.9
			North America					Oceania					South America				
			5th	25th	median	75th	90th	5th	25th	median	75th	90th	5th	25th	median	75th	90th
	Paris Forever	2050	2.4	2.7	3.1	3.4	3.7	1.4	1.5	1.7	1.9	2.1	1.4	1.5	1.7	1.9	2.1
		2075	2.9	3.4	3.9	4.3	4.8	1.7	2.0	2.2	2.5	2.8	1.7	2.0	2.2	2.5	2.8
		2100	3.6	4.3	4.9	5.4	6.1	2.2	2.5	2.8	3.1	3.6	2.2	2.5	2.8	3.1	3.6
		2125	4.4	5.2	6.0	6.6	7.5	2.6	3.1	3.5	3.9	4.5	2.6	3.1	3.5	3.9	4.5
		2150	5.2	6.2	7.0	7.8	8.8	3.1	3.7	4.1	4.6	5.4	3.1	3.7	4.1	4.6	5.4
	Paris2C	2050	2.3	2.6	3.0	3.3	3.6	1.3	1.5	1.7	1.9	2.1	1.3	1.5	1.7	1.9	2.1
		2075	2.6	3.0	3.4	3.8	4.2	1.5	1.8	2.0	2.2	2.5	1.5	1.8	2.0	2.2	2.5
		2100	2.6	3.0	3.4	3.8	4.2	1.6	1.8	2.0	2.3	2.6	1.6	1.8	2.0	2.3	2.6
		2125	2.6	3.0	3.4	3.8	4.2	1.6	1.8	2.0	2.3	2.6	1.6	1.8	2.0	2.3	2.6
		2150	2.6	3.0	3.4	3.8	4.2	1.6	1.8	2.1	2.3	2.6	1.6	1.8	2.1	2.3	2.6

			Africa					Asia					Europe				
			5th	25th	median	75th	90th	5th	25th	median	75th	90th	5th	25th	median	75th	90th
JJA	Paris Forever	2050	1.7	1.9	2.1	2.3	2.5	1.8	1.8	2.0	2.2	2.1	1.6	1.6	1.8	2.0	1.8
		2075	2.2	2.5	2.8	3.0	3.2	2.3	2.4	2.6	2.9	2.9	2.1	2.1	2.4	2.7	2.6
		2100	2.7	3.1	3.5	3.8	4.2	2.9	3.0	3.4	3.7	3.8	2.7	2.7	3.1	3.5	3.6
		2125	3.3	3.9	4.3	4.7	5.1	3.6	3.8	4.2	4.5	4.8	3.3	3.5	4.0	4.4	4.5
		2150	3.9	4.6	5.0	5.5	6.1	4.2	4.5	5.0	5.4	5.7	3.9	4.2	4.7	5.2	5.4
	Paris2C	2050	1.7	1.9	2.1	2.3	2.4	1.8	1.8	2.0	2.2	2.1	1.6	1.5	1.8	2.0	1.8
		2075	1.9	2.2	2.4	2.6	2.8	2.0	2.0	2.3	2.5	2.4	1.8	1.7	2.0	2.3	2.1
		2100	1.9	2.2	2.4	2.7	2.9	2.0	2.0	2.3	2.5	2.5	1.8	1.8	2.1	2.3	2.3
		2125	1.9	2.2	2.4	2.7	2.9	2.0	2.0	2.3	2.5	2.5	1.8	1.7	2.1	2.3	2.2
		2150	1.9	2.2	2.4	2.7	2.9	2.0	2.0	2.3	2.5	2.5	1.8	1.7	2.1	2.3	2.2
			North America					Oceania					South America				
			5th	25th	median	75th	90th	5th	25th	median	75th	90th	5th	25th	median	75th	90th
	Paris Forever	2050	1.8	1.7	2.0	2.2	2.0	1.4	1.6	1.8	2.0	2.2	1.4	1.6	1.8	2.0	2.2
		2075	2.3	2.3	2.6	2.8	2.8	1.8	2.0	2.3	2.6	3.0	1.8	2.0	2.3	2.6	3.0
		2100	2.8	2.9	3.3	3.6	3.7	2.2	2.6	2.9	3.3	3.8	2.2	2.6	2.9	3.3	3.8
		2125	3.5	3.7	4.1	4.5	4.7	2.7	3.2	3.6	4.1	4.7	2.7	3.2	3.6	4.1	4.7
		2150	4.1	4.4	4.9	5.3	5.6	3.2	3.8	4.3	4.8	5.6	3.2	3.8	4.3	4.8	5.6
	Paris2C	2050	1.7	1.7	1.9	2.1	2.0	1.3	1.5	1.7	2.0	2.2	1.3	1.5	1.7	2.0	2.2
		2075	1.9	1.9	2.2	2.5	2.4	1.6	1.8	2.1	2.3	2.7	1.6	1.8	2.1	2.3	2.7
		2100	1.9	1.9	2.2	2.5	2.4	1.6	1.8	2.1	2.4	2.7	1.6	1.8	2.1	2.4	2.7
		2125	1.9	1.9	2.2	2.4	2.4	1.6	1.8	2.1	2.4	2.7	1.6	1.8	2.1	2.4	2.7
		2150	1.9	1.9	2.2	2.4	2.4	1.6	1.9	2.1	2.4	2.7	1.6	1.9	2.1	2.4	2.7

Table 7. Summary of results from the *Paris Forever* and *Paris2C* scenarios for precipitation change averaged over major continental regions. For each region, percentile values are provided for the annual, December-February (DJF) and June-August (JJA) averaged change.

			Africa					Asia					Europe				
			5th	25th	median	75th	90th	5th	25th	median	75th	90th	5th	25th	median	75th	90th
Annual	Paris Forever	2050	-17.2	6.7	22.5	36.0	50.3	30.2	37.3	47.6	57.9	65.6	8.9	14.3	22.0	33.9	45.5
		2075	-23.9	8.5	29.6	48.0	68.1	41.9	52.4	65.3	78.6	90.8	9.4	17.2	26.7	42.8	59.7
		2100	-30.9	10.8	38.4	62.7	90.7	56.4	70.8	87.3	104.8	124.4	9.7	19.6	31.7	52.4	75.4
		2125	-36.9	15.0	49.6	80.9	118.4	72.1	90.9	111.4	133.1	160.5	11.5	22.9	37.9	63.8	93.3
		2150	-40.4	19.7	61.4	100.2	148.4	89.4	112.0	136.2	162.8	198.3	14.4	26.6	45.2	76.3	113.5
	Paris2C	2050	-17.0	6.6	21.9	35.0	49.0	30.9	37.6	47.9	58.1	65.7	9.5	14.7	22.1	33.9	45.1
		2075	-18.7	8.6	26.4	41.9	59.0	39.0	47.0	58.1	69.6	79.6	11.4	17.8	25.9	39.8	53.5
		2100	-18.4	9.7	28.2	44.3	62.2	40.7	49.1	60.8	72.4	82.7	12.1	18.8	27.2	41.5	55.6
		2125	-17.8	10.4	28.7	44.9	62.8	39.6	48.5	59.7	71.6	82.3	12.4	19.0	27.2	41.5	55.8
		2150	-18.3	10.3	28.6	44.9	62.7	40.2	48.7	60.1	71.8	82.0	12.4	19.1	27.6	41.6	56.2

			North America					Oceania					South America				
			5th	25th	median	75th	90th	5th	25th	median	75th	90th	5th	25th	median	75th	90th
Annual	Paris Forever	2050	9.6	19.2	30.5	41.1	54.1	-24.5	-7.4	18.4	40.7	62.4	-24.5	-7.4	18.4	40.7	62.4
		2075	14.1	27.8	42.1	55.4	74.7	-30.1	-5.8	26.7	55.2	88.0	-30.1	-5.8	26.7	55.2	88.0
		2100	20.9	38.3	56.1	72.9	100.7	-32.7	-0.9	37.5	73.8	116.6	-32.7	-0.9	37.5	73.8	116.6
		2125	30.0	51.4	73.0	93.8	129.7	-37.4	6.2	52.7	97.6	157.6	-37.4	6.2	52.7	97.6	157.6
		2150	41.6	65.7	91.0	115.3	158.8	-37.9	19.1	73.2	127.8	202.2	-37.9	19.1	73.2	127.8	202.2
	Paris2C	2050	10.2	19.8	30.9	41.1	54.2	-24.6	-7.9	17.3	39.2	60.3	-24.6	-7.9	17.3	39.2	60.3
		2075	14.9	26.6	39.6	51.5	67.9	-22.9	-2.0	27.5	53.3	82.5	-22.9	-2.0	27.5	53.3	82.5
		2100	15.2	26.8	39.8	51.6	68.4	-20.3	0.1	29.5	55.4	84.3	-20.3	0.1	29.5	55.4	84.3
		2125	14.8	26.6	39.4	51.3	68.2	-18.0	2.8	32.6	58.8	88.5	-18.0	2.8	32.6	58.8	88.5
		2150	14.7	26.3	39.5	51.1	68.0	-15.5	4.7	34.5	61.0	88.7	-15.5	4.7	34.5	61.0	88.7

			Africa					Asia					Europe				
			5th	25th	median	75th	90th	5th	25th	median	75th	90th	5th	25th	median	75th	90th
DJF	Paris Forever	2050	-15.3	3.1	17.5	32.6	44.8	23.4	30.7	41.5	51.7	62.3	23.3	36.8	49.1	64.1	91.5
		2075	-19.5	4.8	23.1	44.0	63.6	30.9	41.7	55.7	68.9	84.0	26.9	46.7	62.5	80.9	119.2
		2100	-22.7	8.3	29.9	56.8	87.0	39.4	54.8	72.5	89.6	111.5	27.9	55.4	75.3	98.7	148.4
		2125	-26.5	11.8	38.3	71.8	117.4	49.8	69.9	92.3	113.9	143.7	29.7	66.8	91.1	121.1	184.3
		2150	-26.4	19.4	49.6	90.8	154.2	60.6	86.4	112.8	139.1	179.1	32.7	80.5	109.9	145.2	223.3
	Paris2C	2050	-15.6	2.5	16.7	31.5	42.9	23.3	30.4	40.8	50.7	61.1	23.1	36.5	48.5	63.0	89.9
		2075	-15.4	5.0	21.4	38.9	54.8	27.9	36.5	48.5	60.1	72.7	26.9	42.9	56.5	73.2	105.8
		2100	-11.6	9.1	25.7	43.9	60.4	29.0	38.2	50.4	62.4	76.2	27.9	44.4	58.5	75.7	109.0
		2125	-9.5	11.3	27.9	45.9	63.2	28.7	37.7	50.0	62.0	75.8	27.8	44.4	58.4	75.4	108.5
		2150	-8.6	12.5	28.9	47.2	64.2	28.6	37.9	50.1	61.8	76.0	28.0	44.7	58.7	75.6	109.4

			North America					Oceania					South America				
			5th	25th	median	75th	90th	5th	25th	median	75th	90th	5th	25th	median	75th	90th
DJF	Paris Forever	2050	22.3	31.4	45.5	58.5	74.7	-76.8	-20.3	29.3	66.8	182.4	-76.8	-20.3	29.3	66.8	182.4
		2075	31.2	42.8	60.9	78.5	101.5	-99.6	-20.9	40.8	89.9	240.3	-99.6	-20.9	40.8	89.9	240.3
		2100	41.0	56.4	78.6	101.7	133.6	-119.3	-20.7	56.0	113.9	315.0	-119.3	-20.7	56.0	113.9	315.0
		2125	53.2	73.3	99.8	130.1	171.9	-131.6	-15.9	75.1	148.6	390.0	-131.6	-15.9	75.1	148.6	390.0
		2150	66.8	91.3	122.9	161.0	213.6	-133.2	-3.1	101.9	189.1	488.1	-133.2	-3.1	101.9	189.1	488.1
	Paris2C	2050	22.4	31.2	44.9	57.7	73.5	-75.4	-20.3	27.8	64.8	174.7	-75.4	-20.3	27.8	64.8	174.7
		2075	28.9	39.3	55.4	70.8	90.5	-81.6	-13.8	42.8	87.4	219.8	-81.6	-13.8	42.8	87.4	219.8
		2100	29.3	39.7	56.0	71.4	91.6	-78.3	-10.3	46.7	90.5	227.6	-78.3	-10.3	46.7	90.5	227.6
		2125	28.8	39.3	55.4	70.5	90.7	-73.1	-4.3	52.2	96.7	230.7	-73.1	-4.3	52.2	96.7	230.7
		2150	28.9	39.2	55.4	70.7	90.9	-70.9	-1.6	55.3	100.6	237.5	-70.9	-1.6	55.3	100.6	237.5

			Africa					Asia					Europe				
			5th	25th	median	75th	90th	5th	25th	median	75th	90th	5th	25th	median	75th	90th
JJA	Paris Forever	2050	-32.7	5.5	25.5	42.0	68.9	23.8	30.5	50.5	70.9	80.6	-17.8	-12.0	0.0	16.8	27.1
		2075	-47.8	7.0	32.7	53.5	94.4	33.9	47.0	70.8	96.1	114.9	-29.7	-17.5	-2.7	18.7	34.7
		2100	-64.1	10.2	42.2	69.3	124.9	48.7	70.5	98.9	129.6	158.6	-46.9	-25.5	-7.7	19.6	41.8
		2125	-79.5	14.9	55.5	89.8	163.6	57.8	91.2	124.3	161.9	204.2	-62.7	-32.5	-11.7	22.0	51.7
		2150	-96.5	18.4	66.5	109.1	202.1	70.9	114.6	153.3	198.0	250.8	-79.8	-38.9	-14.5	24.5	59.7
	Paris2C	2050	-31.8	5.7	25.2	41.0	66.9	24.6	31.3	51.2	72.4	81.7	-17.4	-11.3	0.9	17.2	27.0
		2075	-38.1	6.7	28.9	47.1	80.2	35.4	44.5	65.3	88.3	101.6	-20.5	-11.7	1.2	20.3	32.8
		2100	-41.0	5.6	28.5	47.2	81.3	37.5	47.6	69.3	91.7	103.2	-23.0	-13.0	1.0	20.4	33.3
		2125	-42.3	4.9	27.6	46.3	80.3	35.8	45.2	67.0	89.6	102.3	-22.4	-12.1	1.6	20.9	33.7
		2150	-42.8	4.3	27.2	46.0	80.8	37.7	46.8	67.6	89.8	102.6	-22.7	-12.7	1.5	20.8	34.5

			North America					Oceania					South America				
			5th	25th	median	75th	90th	5th	25th	median	75th	90th	5th	25th	median	75th	90th
JJA	Paris Forever	2050	-28.0	-21.1	-1.7	16.7	26.8	-40.1	-24.1	7.8	46.8	83.7	-40.1	-24.1	7.8	46.8	83.7
		2075	-37.0	-24.3	0.5	24.0	41.4	-51.8	-26.5	15.1	64.0	118.4	-51.8	-26.5	15.1	64.0	118.4
		2100	-46.2	-27.2	3.7	33.0	58.4	-67.5	-28.5	23.8	80.9	154.2	-67.5	-28.5	23.8	80.9	154.2
		2125	-55.7	-28.9	7.0	42.0	78.3	-82.7	-28.5	36.8	105.3	197.9	-82.7	-28.5	36.8	105.3	197.9
		2150	-63.0	-29.3	9.7	52.1	97.9	-95.2	-24.3	52.9	132.6	246.1	-95.2	-24.3	52.9	132.6	246.1
	Paris2C	2050	-26.0	-19.3	-0.2	17.9	28.0	-38.5	-23.8	7.8	46.1	82.2	-38.5	-23.8	7.8	46.1	82.2
		2075	-28.9	-18.4	4.1	24.5	38.4	-42.3	-21.8	15.2	59.1	105.8	-42.3	-21.8	15.2	59.1	105.8
		2100	-28.9	-18.2	4.2	25.1	38.6	-43.0	-21.3	16.6	60.6	108.2	-43.0	-21.3	16.6	60.6	108.2
		2125	-28.9	-18.4	4.0	24.5	38.0	-40.5	-18.8	18.1	62.9	110.7	-40.5	-18.8	18.1	62.9	110.7
		2150	-29.6	-18.7	3.7	24.6	38.4	-38.8	-17.8	19.6	64.2	112.3	-38.8	-17.8	19.6	64.2	112.3

Climate Risk: Transition Risk

Context

Climate change also poses transition risks that arise from shifts in the political, technological, social and economic landscape that are likely to occur during the transition to a low-carbon economy. With growing pressures from society, more and more government and industry actions are moving the world away from "business as usual" and toward decarbonization. Societal pressures and technological trends drive a reinforcing mechanism for action: pressure to pursue low-carbon solutions results in an expanding array of low-carbon options, which in turn generates more pressure to implement those options. However, the pace of transformation can be uneven. There are substantial uncertainties in how future technologies, policies and regulations, national stability, economic growth and other aspects of human development will evolve. With a curtailed resumption of global activities following the Covid-19 pandemic, these uncertainties are even greater.

That said, climate-related transition risks can emerge quickly, even in regions where the climate changes slowly. Since stock prices and investment decisions are forward-looking, financial and economic impacts can rapidly evolve from a slowly evolving climate risk. 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, economy and technologies, and the transmission channels of climate and policy impacts through the economy.

Recent Findings

Transition risks depend on the likelihood of particular policies and their stringency. For example, a rapid transition away from fossil fuels may result in stranded assets, where earnings from fossil fuel assets and resources are reduced or completely lost 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.

One of our earlier studies (Landry *et al,* 2019) estimated that under an emissions pathway similar to that of the *Paris 2°C* scenario in this Outlook, the net present value of global stranded fossil assets (defined as the value of fossil fuel economic output in a policy scenario relative to a no-policy scenario) would be about $17 trillion (**Figure 37**)—more than the current GDP of China and slightly less than the U.S. GDP. Such a rapid transition would also significantly impact household transportation, crops, livestock, forestry, food, energy-intensive industry, other industry, services, commercial transportation and dwelling ownership. In general, prematurely retired fossil capital stock and the need to replace conventional energy sources with more expensive, low-carbon options draws investment resources away from other sectors of the economy. The magnitude of any sectoral impact will depend on the aggressiveness of energy transition policies.

Decision-makers must confront substantial uncertainty not only regarding future policies but also about the technical and financial viability and competitiveness of different low-carbon technologies. We have shown that technology options in a climate mitigation portfolio can differ among countries depending on resource availability, labor and capital costs, technology transfers, openness to international trade and other factors.

A case in point is our analysis of the potential availability of waste carbon dioxide for synthetic hydrocarbon fuel production. These fuels could become important in aviation and other sectors where fuel alternatives are limited. Availability of waste CO_2 depends on the pathways of carbon capture development that can be applied in power generation and industrial processes (cement, iron and steel, chemicals). Deployment of carbon capture, in turn, depends on numerous factors. **Table 8** shows global annual CO_2 volumes available for synthetic fuel production. These volumes vary substantially over time and between policy scenarios. Investors need to consider these transition risks. Similar scenario analysis can be employed for other technologies such as hydrogen, bioenergy with carbon capture and storage (BECCS), and advanced nuclear power.

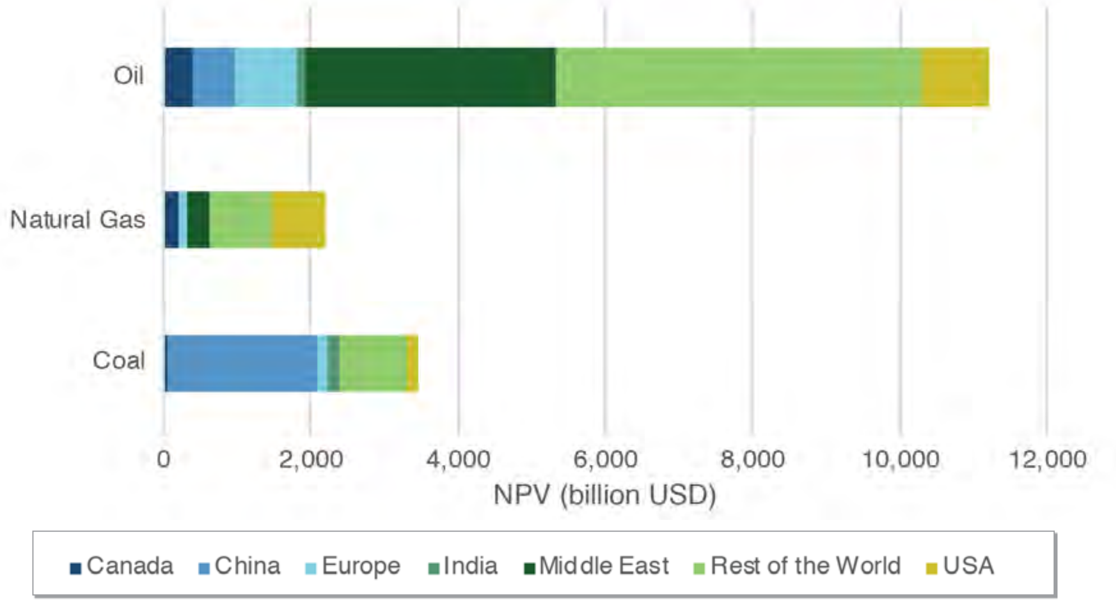

Figure 37. Stranded Value. Net present value (NPV) of economic output lost from fossil fuels not produced through 2040 in the *Paris 2°C* scenario. Data source: Landry *et al* (2019).

Implications

Transition risk assessment can be done for a particular investment type, company, industry or country. While in this Outlook we do not assess the impacts of climate risk on a particular investment portfolio, we do illustrate how a set of scenarios can be used to evaluate particular investment decisions. Transition risk associated with resource rents may be unavoidable, but increasing losses can be avoided by not investing further in developing particular 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 socioeconomic 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 (see Box 5) enables decision-makers to account for both physical and socioeconomic components of climate risks and to quantify uncertainty in assessing transition risks.

More Information

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Table 8. Global annual CO_2 captured ($MtCO_2$ /year) from industrial processes and power generation in different scenarios. Data source: Morris *et al* (2020), Farrell (2018).

	2030			2050			2070		
	Total	Gas CCS	Coal CCS	Total	Gas CCS	Coal CCS	Total	Gas CCS	Coal CCS
Power Generation: $10/tCO₂ initial tax	0	0	0	0	0	0	16	0	16
Power Generation: $30/tCO₂ initial tax	4	4	0	748	7	741	8150	63	8087
Power Generation: $60/tCO₂ initial tax	633	25	608	5922	130	5792	9688	964	8725
Cement Production: $60/tCO₂ initial tax	13			325			1470		
Steel Production: $60/tCO₂ initial tax	15			373			1429		

Box 5.

Representing Uncertainty

The MIT Joint Program developed the Greenhouse Gamble™ wheels to convey uncertainty in climate change prediction, which is driven by uncertainty in both the human system (e.g. economic and population growth, energy use, emissions, etc.) and the Earth system (e.g. the climate's response to emissions). The roulette-style spinning wheels show the estimated probability of potential change in global average surface temperature at the end of the century (2091–2100) compared to pre-industrial levels (1861–1880). Each wheel represents a different set of greenhouse gas policies, and the relative area that each colored slice occupies within the wheel shows the likelihood of temperature change in that range. **Figure 38** provides temperature outcomes under four policy scenarios. These wheels illustrate that one of the main objectives of climate policy is to lower (or eliminate) the likelihood of extreme temperature outcomes. Additional information about the Greenhouse Gamble and the scenarios represented in Figure 38 is available at:

https://globalchange.mit.edu/research/research-tools/risk-analysis/greenhouse-gamble

The policy behind the 2°C Policy wheel is designed to achieve 2°C with a 66% probability, not a 50% probability like the Paris 2°C scenario in this Outlook.

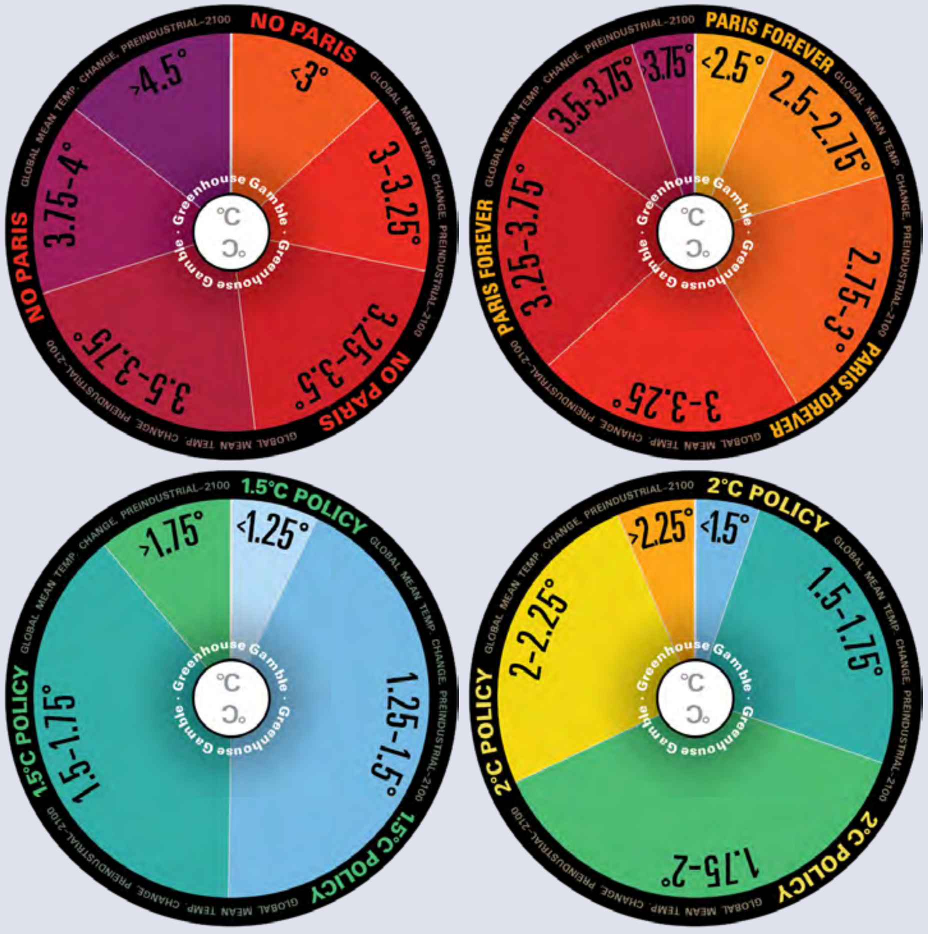

Figure 38. Temperature outcomes under four policy scenarios

Policy Prospects

Prospects for Meeting Short-Term Paris Goals

Under the 2015 Paris Agreement, each participating country's Nationally Determined Contribution (NDC) includes a pledged achievement in greenhouse gas emissions reduction, by 2030 for nearly all signatories. The Agreement established a five-year ratchet of increasing effort, so in 2020 all the parties were to review their NDCs with the objective of setting more ambitious goals. Also, in 2020 they were to submit plans for decarbonizing their economies in the longer term, and to address unresolved conficts over the Agreement's rules and procedures. The Fall 2020 meeting of its Conference of Parties (COP) was thus a crucial point in implementation of the Agreement. Then came the Covid-19 pandemic, severe economic disruption, and postponement of the 2020 COP to 2021—clouding the outlook for emissions reductions in the near term.

Though largely limited to information from before the pandemic, estimates are available of progress toward meeting these first NDCs. For example, in its 2020 Emissions Gap Report, the UN Environmental Program (UNEP) evaluated the emissions control packages of the G20 nations, grading each for adequacy. Thirteen of the 20 were projected to meet their NDCs with currently implemented policies. Five, including the U.S., were judged to need additional measures, and insufficient information was available to evaluate the final two.

Obvious qualifications apply to these early assessments, prepared after only five years on the path to what amounts to a 15-year task. Still, the outlook in 2020 was encouraging. Just the 13 nations that the UNEP found to be on track to meet their pledges account for around 60% of 2020 greenhouse gas emissions.

Impacts of Covid-19

The global health and economic crisis introduced additional uncertainties in the prospects for 2030. Most important are the lingering economic impacts of the pandemic on the ability of nations to meet their existing targets, and perhaps augment them. Its likely macroeconomic effect is to ease the task, because several years of Covid-induced recession will, for many nations, decrease the emissions reductions required to meet their NDCs. Adding to this growth impact on emissions are the potential microeconomic effects. One likely legacy of the pandemic: lasting reductions in auto and air travel, and associated fuel use and fossil emissions, largely due to increased telecommuting and teleconferencing. Other shifts in patterns of personal consumption, delivery services and global supply chains could have plus or minus effects. Taken all together, however, the microeconomic effects of Covid-19 would appear to further ease the burden of meeting the existing Paris pledges.

Harder to judge is the effect of the current economic downturn and associated political disruption on the priority nations will give to the global climate threat and their Paris pledges, and thus on next steps in implementation of the Paris Agreement. By the close of the first quarter of 2021 only 10 nations and the EU had submitted updated NDCs indicating increased ambition, and only around 30 had submitted long-term strategies. Putting these processes back on track in time for the 2021 COP in Glasgow will be crucial for the future of the Agreement. Also, completion of the rules and procedures under the Agreement is stalled by the disruption. Most important are the rules under Article 6, which defines the ways parties can cooperate in meeting their NDCs, including carbon markets. Until face-to-face negotiations are possible, it is unlikely the disagreements surrounding this Article can be resolved.

Reasons for Optimism

On the other hand, there are encouraging signs of increased commitments by several of the largest greenhouse gas emitters. China's president has pledged carbon neutrality for his nation by 2060, and several others, including the U.S., have declared a similar intention for all greenhouse gases by 2050. Paths to these mid-century targets call for additional short-term effort. For example, the EU has increased its 2030 NDC from a 40% to a 55% reduction. Also, at a summit of world leaders on Earth Day 2021, the Biden Administration announced a much more ambitious U.S pledge, a 50-52% reduction by 2030, and leaders of several other nations said they would take on greater emissions cuts—all statements likely to be implemented in revised NDCs in time for the 2021 COP.

The emissions projections in the *Paris Forever* scenario take account of the pandemic's effect on economic growth and assume that all nations just meet their current (as of March 2021) NDCs under these conditions. The result is stabilization of global greenhouse gas emissions over the years to 2030. With the prospect that Covid-19's effects may further lower the effort required to meet existing pledges, and the announced increase in ambition by several large emitters, it is likely that the world's collective efforts will not only stabilize global emissions over the short term, but start them on a declining path.

More Information

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Prospects for Meeting Long-Term Paris Goals

The long-term goal of international negotiations on climate change is stabilization of atmospheric concentrations of GHG emissions and, as a result, the average global temperature. The United Nations Framework Convention on Climate Change (UNFCCC) entered into force in 1994 and set out principles on how to assess a timeframe for and level of stabilization, but did not indicate a specific target or path. To operationalize this long-term goal required more input from the scientific community on the level and nature of climate change associated with different stabilization levels, and the ability of humans, ecosystems, agriculture and the world's economies to adapt to such changes. The succeeding reports of the Intergovernmental Panel on Climate Change (IPCC) have been charged to establish scientific foundations for targets and timetables needed to meet the overarching goal of the UNFCCC.

Based on this growing set of information, the 21st UNFCCC Conference of the Parties (COP21) meeting in Paris in 2015 established more precise temperature targets by agreeing to 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."

While our *Paris Forever* scenario represents an unprecedented global commitment to limit greenhouse gas emissions, it neither stabilizes climate nor limits climate change. We therefore consider two additional scenarios that align with the Paris Agreement's long-term temperature targets. Referred to as *Paris 2°C* and *Paris 1.5°C*, these scenarios aim to limit and stabilize human-induced global climate warming to 2°C and 1.5°C, respectively, by the end of this century, with a 50% probability. Taking a probabilistic approach with our Integrated Global System Modeling (IGSM) framework enables us to quantify the range of global climate response to given emissions pathways consistent with the temperature stabilization targets (see Figure 29). This allows us to evaluate these scenarios through a risk-based approach.

Radiative Forcing and Climate Pathways

By design, through the course of the current decade, the *Paris 2°C* and *Paris 1.5°C* mitigation scenarios are indistinguishable in terms of the increased radiative forcing and global CO_2 concentrations within the climate system (**Figure 39**). However, starting in the 2030s, these pathways diverge abruptly. Looking at radiative forcing, the *Paris 1.5°C* sharply turns to a nearly monotonic decline through the remainder of the 21st century, and then remains constant through the middle of the next century. In contrast, the climate forcing in the *Paris 2°C* scenario continues to rise going into the latter half of this century, when it gradually begins to decline. Generally speaking, global CO_2 concentrations show very similar features with the notable exception that in the *Paris 1.5°C* scenario, the decreasing trend through the 21st century is not as prominent as its radiative-forcing counterpart.

Another important distinction between these two scenarios is that by 2100, climate forcing in the *Paris 1.5°C* must decline to levels that are approximately 10% below what the planet is currently experiencing. This is not required in the *Paris 2°C* scenario, which can peak at values 30% higher than present levels through the 2070s, but then must eventually subside to values 15–20% higher than present levels by 2100 and into middle of next century.

In both mitigation scenarios, temperatures will continue to rise through the next two decades (**Figure 40**). Any differences between the scenarios are indistinguishable up through the middle of the 2030s. By the 2040s, the scenarios deviate, primarily due to the *Paris 1.5°C* scenario having met its global climate-warming target. An important takeaway from *Paris 1.5°C* is that while the global temperature response has leveled off by mid-century, the climate forcing (and corresponding emissions) must continue to decline through the entire course of the 21st century. To a lesser extent, this is also seen in the *Paris 2°C* scenario, where the global temperature response levels off by 2090, but forcing must continue on a downward trend in the decades that follow (and into the 22nd century). The *Paris 2°C* scenario also indicates that even among all the plausible outcomes captured by the IGSM ensemble, there is no likelihood of even the "coolest" trajectories to remain below 1.5°C at the end of the century. On the other hand, the *Paris 1.5°C* ensemble scenario can virtually assure the world of remaining below 2°C of global-averaged warming. In the

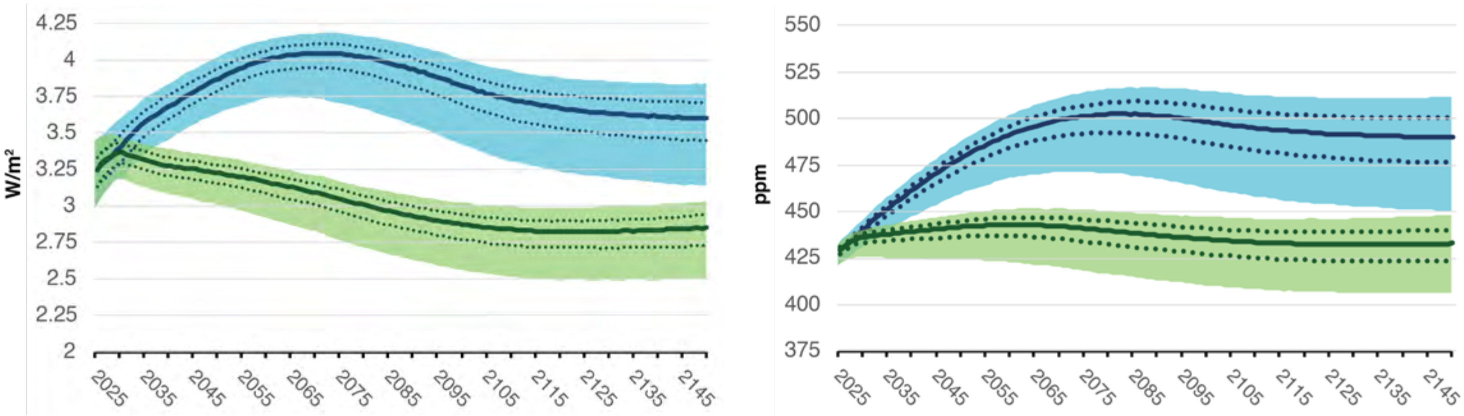

Figure 39. Total radiative forcing (W/m^2, left panel) and global CO_2 concentration (ppm, right panel) that results from EPPA emissions of greenhouse gases, based on the *Paris 2°C* (blue shading/lines) and *Paris 1.5°C* (green shading/lines) ensemble scenarios. Values are calculated from a baseline 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.

Accelerated Actions scenario where net anthropogenic GHG emissions are set to zero after 2070, global temperature is further reduced from the *Paris 1.5°C* trajectory and approaches 1°C by the middle of the 22nd century (though not shown in Figure 40).

As noted in the IGSM's *Paris Forever* scenario, the global hydrologic sensitivity forms the basis for the rise in global precipitation (**Figure 41**) with any corresponding global temperature increase. By this measure, the current global precipitation rate is estimated to be approximately 2.3% higher than pre-industrial conditions. As previously shown (Figure 32), under the *Paris Forever* 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 0.2 to 0.35 mm/day, or 7–12% higher than the pre-industrial level. The *Paris 2°C* and *Paris 1.5°C* scenarios not only stabilize the precipitation increase (by 2060 in *Paris 1.5°C* and 2100 in *Paris 2°C*), but substantially reduce the magnitude and potential range of increases. *Paris 2°C* cuts the increases by half and *Paris 1.5°C* reduces them to almost a third of the *Paris Forever* precipitation changes.

Why are these mitigation effects important? The most recent observational evidence as well as climate model estimates tell us that the hydrologic sensitivity of total precipitation from heavy and extreme precipitation events can be 5–10 times that of global mean precipitation. Thus, any global increase in precipitation conveys amplified risk of flooding. The IGSM scenarios indicate there is unavoidable, heightened risk in this regard—and that the world will need to fortify infrastructure and adapt systems that are at risk. However, aggressive mitigation can considerably reduce risk and uncertainty in the proportion (and cost) of adaptive actions.

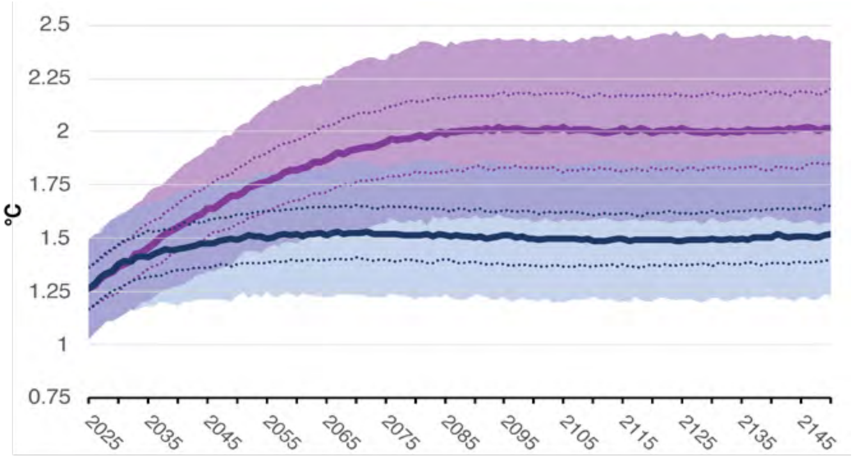

Figure 40. Annual, global temperature changes (°C) based on the MIT IGSM ensemble projections of the *Paris 2°C* (purple shading/lines) and *Paris 1.5°C* (blue shading/lines) scenarios. Changes are calculated from the 1861–1880 mean. In each panel, the solid line represents the median result; the dashed lines denote the interquartile range; and the shaded region depicts the 5th to 95th percentile range of values.

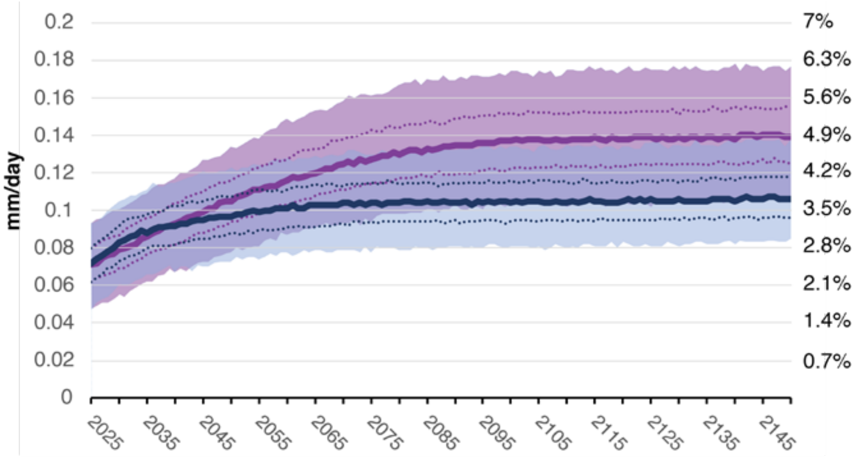

Figure 41. Annual, global precipitation changes (mm/day) based on the MIT IGSM ensemble projections of the *Paris 2°C* (purple shading/lines) and *Paris 1.5°C* (blue shading/lines) scenarios. Changes are calculated from the 1861–1880 mean. In each panel, the solid line represents the median result; the dashed lines denote the interquartile range; and the shaded region depicts the 5th to 95th percentile range of values. The right-hand axis also provides the global precipitation change as a percentage (to the nearest 0.1%) of the 1861–1880 baseline average (= 2.86 mm/day).

Sea-Level Rise and Ocean Acidity

Among the most costly and dangerous risks associated with human-induced warming will be the threats associated with global sea-level rise (GSLR). While the physical mechanisms that are associated with human-induced warming causing GSLR are well understood, the models and numerical tools used by the scientific community to provide quantitative or more granular projections must still account for deep uncertainties and limitations that include: global climate sensitivity, regional hydro-climatic change across the cryosphere, as well as ice-sheet ablation and dynamics. Nevertheless, aligning GSLR estimates to our IGSM Outlook projections, there is an irrefutable risk reduction in the end-of-century GSLR associated with the *Paris 2°C* and *Paris 1.5°C* scenarios. These aggressive mitigation scenarios imply that the probability of end-of-century GSLR exceeding 1 meter is 10–20%, whereas under *Paris Forever* this probability could rise as high as 90%.

Other recent research syntheses have combined observational evidence and Earth-system model-based projections to assess the risk of ocean acidification under a range of future climates. Using these syntheses and extrapolating to our *Paris Forever* scenario, we expect that ocean acidity by the end of this century will likely (i.e., median result) increase by as much as 60%. However, under the *Paris 1.5°C* and *Paris 2°C*, end-of-century indications are that increases in ocean acidification would be reduced to 10%—and begin to rebound under *Paris 1.5°C* going into the next century.

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Preparing for Tomorrow Today: Physical and Transition Risks

Achieving the world's aggressive, long-term goal of keeping the global average surface temperature increase well below 2 degrees Celsius from its preindustrial level will dramatically reduce the physical risks posed by climate change.

These risks are not just looming in the future but have already become evident today. The world is getting warmer, the atmosphere more humid, and climate extremes more intense and frequent. Arctic summer sea ice is disappearing more quickly; the Greenland and Antarctic ice sheets are receding faster; tropical cyclones are intensifying and moving more slowly, creating larger storm surges and precipitation events and more severe flooding; and droughts, extreme heat events and wildfires are intensifying. These trends, on scales from local to global, are now impacting—and in coming decades are likely to further impact—vulnerable infrastructure, supply chains and human health, and to induce widespread famine and migration.

While the long-term goals of the Paris Agreement suggest that world leaders have taken these physical risks seriously, the near-term targets in the accord are largely not on track to meet those long-term goals without an abrupt change in direction very soon.

The transition of the world to net zero emissions comes with major new local-to-global risks and challenges that must be met. This transition involves shifts on political, social, technological and economic fronts, and comes with new challenges for financing and economies, from stranded fossil-fuel assets to stranded workers needing retraining. We will need to strike the optimal balance between the risk of over-investing in the near-term in today's green technologies that will ultimately be superseded, versus the risk of under-investing in these technologies and subsequently needing to rapidly reduce greenhouse gas emissions with the resultant economic shocks.

Lowering these "transition risks" toward net-zero emissions economies will involve integration of both physical and transitional components, a process that requires new models and frameworks. The goal is to empower decision-makers in government and industry to lower the transition risks as an integral companion to mitigation strategies. Financial institutions and regulators will also need to get involved. In addition, we will need to invest more and more in adaptation along with mitigation to lower both physical and transition risks.

Finally, the solutions to these challenges need to be affordable and equitable for all people and all nations. The poorest countries are the most vulnerable and the least responsible for climate change. And the Covid-19 pandemic superimposed on climate change has exposed the compounding effects of multiple stresses on these same vulnerable populations.

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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/Outlook2021

MIT Global Change Outlook 2021 **Projection Data Tables**

Region: World **Scenario: Paris Forever**

		Units	2015	2020	2025	2030	2035	2040	2045	2050
Economic Indicators	GDP	bil 2015 $	80601.2	85686.7	100865.1	114446.2	128591.0	144561.6	160958.7	179157.4
	Consumption	bil 2015 $	45636.7	47307.9	56408.3	64103.0	71911.1	80896.6	89995.2	100020.6
	GDP growth	% / yr	2.6	1.2	3.3	2.6	2.4	2.4	2.2	2.2
	Population	millions	7379.8	7794.8	8184.4	8548.5	8887.5	9198.9	9481.8	9735.0
	GDP *per capita*	2015 $	10921.8	10992.8	12324.0	13387.9	14468.7	15715.2	16975.5	18403.4
GHG Emissions	CO_2 – fossil	Mt CO_2	32616.2	31337.4	32546.5	32178.7	32489.5	32733.7	33915.0	35218.2
	CO_2 – industrial	Mt CO_2	2350.1	2393.6	2439.2	2347.5	2024.8	1904.0	1900.7	1875.9
	CH_4	Mt	352.3	328.4	332.2	320.1	323.2	332.1	340.3	349.0
	N_2O	Mt	9.7	10.7	9.9	10.0	10.3	11.0	11.7	12.4
	PFCs	kt CF_4	22.4	9.5	7.3	5.9	6.0	6.1	6.1	6.3
	SF_6	kt	8.2	5.9	5.8	5.4	5.1	4.9	4.7	4.5
	HFCs	kt HFC-134a	401.8	332.1	323.1	301.2	361.2	423.9	464.6	489.3
	Total GHG net of Land Use	Mt CO_2e	48267.3	46400.1	47512.6	46687.3	46930.4	47566.6	49205.9	50927.7
	CO_2 – land use change	*Mt CO_2*	*1737.7*	*1460.4*	*938.9*	*851.2*	*647.8*	*483.3*	*452.5*	*414.2*
Primary Energy Use	Coal	EJ	162.6	151.1	149.4	147.0	141.9	137.8	139.7	140.9
	Oil	EJ	185.4	184.3	197.6	198.4	200.9	204.2	206.5	210.5
	Bioenergy	EJ	47.2	47.5	48.6	49.4	49.7	50.3	49.2	49.0
	Gas	EJ	125.2	125.7	140.5	143.0	153.3	160.2	174.3	190.9
	Nuclear	EJ	22.9	23.8	24.7	26.9	25.7	25.5	24.9	24.7
	Hydro	EJ	35.8	38.1	39.3	41.7	43.9	46.0	47.7	48.9
	Renewables	EJ	9.0	19.2	34.4	52.0	72.0	98.3	102.6	107.9
Electricity Production	Coal	TWh	9332.5	8253.5	7443.4	6556.2	5841.0	5295.6	5161.5	5030.3
	Oil	TWh	1077.4	865.6	853.6	670.0	668.0	693.9	738.6	769.9
	Gas	TWh	5426.7	5717.9	7340.3	8076.2	8719.6	8800.0	10108.0	11788.4
	Nuclear	TWh	2545.6	2695.0	2830.6	3130.1	3037.9	3065.8	3028.7	3049.7
	Hydro	TWh	3985.8	4308.3	4507.1	4853.5	5197.6	5525.3	5812.1	6050.0
	Renewables	TWh	1002.5	2172.4	3943.1	6058.8	8518.9	11799.5	12505.1	13354.1
	Biofuels	TWh	613.2	706.9	857.1	933.3	995.9	1060.0	1105.9	1153.0
Land Use	Cropland	Mha	1482.1	1487.8	1525.4	1589.6	1598.6	1595.3	1595.1	1592.7
	Bioenergy & Renewables	Mha	38.9	44.1	51.5	53.6	54.9	56.2	57.5	60.7
	Pasture	Mha	1779.9	1780.4	1755.1	1742.1	1742.9	1754.7	1772.8	1782.9
	Managed forest	Mha	748.9	743.3	737.7	698.0	699.4	701.0	694.9	696.0
	Natural grassland	Mha	1490.7	1494.6	1486.6	1478.9	1471.5	1464.8	1458.6	1452.7
	Natural forest	Mha	3174.6	3164.9	3159.0	3153.0	3147.8	3143.0	3136.3	3130.2
	Other	Mha	4097.8	4097.8	4097.8	4097.8	4097.8	4097.8	4097.8	4097.8
Air Pollutant Emissions	SO_2	Tg	104.3	85.9	78.1	67.2	60.4	55.4	51.0	47.4
	NO_x	Tg	122.2	115.4	120.3	120.1	123.7	128.3	132.6	137.7
	Ammonia	Tg	48.5	49.1	55.1	59.2	62.9	67.5	70.6	73.8
	Volatile organic compounds	Tg	147.5	145.1	160.5	167.9	177.5	190.3	200.3	211.5
	Black carbon	Tg	5.0	4.5	4.4	4.2	3.9	3.8	3.6	3.4
	Organic particulates	Tg	11.4	10.4	10.6	10.4	10.0	9.8	9.3	9.0
	Carbon monoxide	Tg	581.6	579.9	647.4	687.2	729.4	782.5	824.1	871.4
Agricultural & food outputs	Crop	bil 2015 $	2416.9	2562.0	2944.8	3351.5	3612.2	3850.8	4099.0	4345.9
	Livestock	bil 2015 $	1885.6	2038.3	2353.2	2635.3	2872.0	3160.4	3415.7	3683.6
	Forest	bil 2015 $	352.4	393.0	479.8	569.5	655.5	761.7	862.7	977.5
	Food	bil 2015 $	7653.8	8150.1	9505.8	10857.1	11901.3	13148.8	14265.3	15486.7
Agricultural & food prices (2020 price = 1)	Crop			1.0	1.1	1.1	1.1	1.1	1.1	1.1
	Livestock			1.0	1.1	1.2	1.3	1.3	1.4	1.4
	Forest			1.0	1.1	1.2	1.2	1.3	1.3	1.3
	Food			1.0	1.0	1.0	1.0	1.0	1.0	1.0
Energy prices (2020 price = 1)	Coal			1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Oil			1.0	1.1	1.1	1.1	1.1	1.1	1.1
	Gas			1.0	1.0	1.0	1.0	1.1	1.1	1.1
	Electricity			1.0	1.1	1.1	1.1	1.1	1.1	1.2

Appendix

MIT Global Change Outlook 2021 | **Projection Data Tables**

Region: World **Scenario: Paris 2°C**

		Units	2015	2020	2025	2030	2035	2040	2045	2050
Economic Indicators	GDP	bil 2015 $	80601.2	85686.7	100865.1	114446.2	126728.5	141020.8	154409.9	166466.8
	Consumption	bil 2015 $	45636.7	47307.9	56408.3	64103.0	71343.2	79685.8	87287.9	94114.7
	GDP growth	% / yr	2.6	1.2	3.3	2.6	2.1	2.2	1.8	1.5
	Population	millions	7379.8	7794.8	8184.4	8548.5	8887.5	9198.9	9481.8	9735.0
	GDP *per capita*	2015 $	10921.8	10992.8	12324.0	13387.9	14259.2	15330.3	16284.9	17099.8
GHG Emissions	CO_2 – fossil	Mt CO_2	32616.2	31337.4	32546.5	32178.7	27279.3	24546.0	21733.6	18605.2
	CO_2 – industrial	Mt CO_2	2350.1	2393.6	2439.2	2347.5	1967.6	1824.5	1776.3	1664.9
	CH_4	Mt	352.3	328.4	332.2	320.1	319.9	312.9	315.2	322.4
	N_2O	Mt	9.7	10.7	9.9	10.0	14.6	14.4	13.9	14.5
	PFCs	kt CF_4	22.4	9.5	7.3	5.9	4.5	4.4	4.4	5.1
	SF_6	kt	8.2	5.9	5.8	5.4	4.0	3.5	3.3	3.1
	HFCs	kt HFC-134a	401.8	332.1	323.1	301.2	248.8	253.7	321.1	352.4
	Total GHG net of Land Use	Mt CO_2e	48267.3	46400.1	47512.6	46687.3	42526.3	39378.1	36541.4	33703.8
	CO_2 – land use change	*Mt CO_2*	1737.7	1460.4	938.9	851.2	649.9	856.7	795.2	728.9
Primary Energy Use	Coal	EJ	162.6	151.1	149.4	147.0	108.4	91.4	78.8	65.8
	Oil	EJ	185.4	184.3	197.6	198.4	187.2	178.0	151.3	113.2
	Bioenergy	EJ	47.2	47.5	48.6	49.4	49.7	50.3	49.5	50.9
	Gas	EJ	125.2	125.7	140.5	143.0	145.7	141.6	147.2	157.6
	Nuclear	EJ	22.9	23.8	24.7	26.9	26.1	27.3	27.4	26.8
	Hydro	EJ	35.8	38.1	39.3	41.7	44.7	47.2	49.2	51.0
	Renewables	EJ	9.0	19.2	34.4	52.0	87.7	126.5	147.5	170.6
Electricity Production	Coal	TWh	9332.5	8253.5	7443.4	6556.2	3946.7	3133.5	2358.4	1535.5
	Oil	TWh	1077.4	865.6	853.6	670.0	458.0	342.7	262.2	42.1
	Gas	TWh	5426.7	5717.9	7340.3	8076.2	8541.4	7510.9	7462.2	8394.5
	Nuclear	TWh	2545.6	2695.0	2830.6	3130.1	3089.8	3282.5	3335.5	3318.4
	Hydro	TWh	3985.8	4308.3	4507.1	4853.5	5289.7	5671.6	5998.1	6314.9
	Renewables	TWh	1002.5	2172.4	3943.1	6058.8	10370.8	15189.8	17973.5	21104.8
	Biofuels	TWh	613.2	706.9	857.1	933.3	968.8	1033.3	1051.5	1171.6
Land Use	Cropland	Mha	1482.1	1487.8	1525.4	1589.6	1598.2	1597.5	1592.8	1585.8
	Bioenergy & Renewables	Mha	38.9	44.1	51.5	53.6	54.4	56.2	59.0	70.1
	Pasture	Mha	1779.9	1780.4	1755.1	1742.1	1739.7	1742.7	1771.2	1786.5
	Managed forest	Mha	748.9	743.3	737.7	698.0	703.2	713.3	702.5	697.4
	Natural grassland	Mha	1490.7	1494.6	1486.6	1478.9	1471.8	1465.3	1458.9	1453.1
	Natural forest	Mha	3174.6	3164.9	3159.0	3153.0	3147.8	3140.1	3130.7	3122.3
	Other	Mha	4097.8	4097.8	4097.8	4097.8	4097.8	4097.8	4097.8	4097.8
Air Pollutant Emissions	SO_2	Tg	104.3	85.9	78.1	67.2	49.8	42.7	36.2	29.0
	NO_x	Tg	122.2	115.4	120.3	120.1	108.4	106.7	100.4	91.2
	Ammonia	Tg	48.5	49.1	55.1	59.2	60.7	63.9	65.3	65.3
	Volatile organic compounds	Tg	147.5	145.1	160.5	167.9	163.2	167.5	166.8	163.7
	Black carbon	Tg	5.0	4.5	4.4	4.2	3.5	3.2	2.9	2.5
	Organic particulates	Tg	11.4	10.4	10.6	10.4	9.3	8.8	8.0	7.1
	Carbon monoxide	Tg	581.6	579.9	647.4	687.2	673.5	696.3	693.1	682.8
Agricultural & food outputs	Crop	bil 2015 $	2416.9	2562.0	2944.8	3351.5	3589.3	3826.5	4057.2	4279.6
	Livestock	bil 2015 $	1885.6	2038.3	2353.2	2635.3	2849.4	3116.5	3366.3	3612.8
	Forest	bil 2015 $	352.4	393.0	479.8	569.5	648.1	747.1	836.4	923.7
	Food	bil 2015 $	7653.8	8150.1	9505.8	10857.1	11871.7	13077.9	14108.3	15131.5
Agricultural & food prices (2020 price = 1)	Crop			1.0	1.1	1.1	1.1	1.0	1.0	1.0
	Livestock			1.0	1.1	1.2	1.3	1.4	1.4	1.4
	Forest			1.0	1.1	1.2	1.2	1.2	1.2	1.2
	Food			1.0	1.0	1.0	1.0	1.0	1.0	1.0
Energy prices (2020 price = 1)	Coal			1.0	1.0	1.0	0.9	0.9	0.8	0.8
	Oil			1.0	1.1	1.1	1.0	1.0	0.9	0.8
	Gas			1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Electricity			1.0	1.1	1.1	1.2	1.2	1.2	1.3

Appendix

MIT Global Change Outlook 2021 **Projection Data Tables**

Region: World **Scenario: Accelerated Actions**

		Units	2015	2020	2025	2030	2035	2040	2045	2050
Economic Indicators	GDP	bil 2015 $	80601.2	85686.7	100653.8	113619.9	126816.4	141538.6	155192.7	167250.7
	Consumption	bil 2015 $	45636.7	47307.9	56238.7	63476.5	70659.0	78786.6	86293.6	92758.1
	GDP growth	% / yr	2.6	1.2	3.3	2.5	2.2	2.2	1.9	1.5
	Population	millions	7379.8	7794.8	8184.4	8548.5	8887.5	9198.9	9481.8	9735.0
	GDP *per capita*	2015 $	10921.4	10990.6	12298.2	13291.2	14269.0	15386.6	16367.4	17180.3
GHG Emissions	CO_2 – fossil	Mt CO_2	32616.2	31337.4	29704.1	25001.7	21173.5	17603.3	13800.7	9925.1
	CO_2 – industrial	Mt CO_2	2350.1	2393.6	2417.9	2296.2	1916.8	1756.1	1687.9	1565.0
	CH_4	Mt	352.3	328.4	310.4	281.2	262.1	249.3	234.2	218.0
	N_2O	Mt	9.7	10.7	8.5	8.1	7.7	7.5	7.2	6.6
	PFCs	kt CF_4	22.4	9.5	3.2	2.8	2.6	2.6	2.2	2.1
	SF_6	kt	8.2	5.9	3.4	3.3	2.9	2.5	2.0	1.8
	HFCs	kt HFC-134a	401.8	332.1	225.9	198.9	202.7	215.5	224.2	225.1
	Total GHG net of Land Use	Mt CO_2e	48267.3	46400.1	43455.7	37663.6	32828.6	28685.6	24302.3	19685.8
	CO_2 – land use change	*Mt CO_2*	1737.7	1460.4	936.6	850.6	610.1	795.5	747.7	680.3
Primary Energy Use	Coal	EJ	162.6	151.1	132.3	96.1	69.5	47.6	31.3	21.1
	Oil	EJ	185.4	184.3	194.3	190.9	181.6	171.0	151.0	113.2
	Bioenergy	EJ	47.2	47.5	48.6	49.4	49.9	50.5	50.0	50.6
	Gas	EJ	125.2	125.7	125.2	114.6	100.5	85.7	73.8	70.1
	Nuclear	EJ	22.9	23.8	24.8	27.2	27.4	32.3	42.7	49.0
	Hydro	EJ	35.8	38.1	39.5	42.5	45.9	48.9	51.9	54.2
	Renewables	EJ	9.0	19.2	36.0	73.9	129.5	178.6	205.3	238.4
Electricity Production	Coal	TWh	9332.5	8253.5	6680.6	4279.1	2068.3	713.4	376.5	339.2
	Oil	TWh	1077.4	865.6	784.7	641.0	510.9	355.1	211.7	45.7
	Gas	TWh	5426.7	5717.9	6925.0	7138.3	5767.6	4249.1	3384.2	3422.7
	Nuclear	TWh	2545.6	2695.0	2846.5	3171.8	3246.0	3872.2	5198.9	6066.1
	Hydro	TWh	3985.8	4308.3	4536.0	4955.2	5434.6	5868.1	6322.2	6710.0
	Renewables	TWh	1002.5	2172.4	4134.6	8611.9	15316.5	21441.6	25015.6	29491.9
	Biofuels	TWh	613.2	706.9	859.5	946.2	1033.9	1117.9	1252.6	1381.7
Land Use	Cropland	Mha	1482.1	1487.8	1530.0	1595.6	1607.6	1606.0	1599.9	1595.5
	Bioenergy & Renewables	Mha	38.9	44.1	51.7	54.8	57.4	59.3	64.7	72.4
	Pasture	Mha	1779.9	1780.4	1744.9	1733.3	1722.5	1725.7	1728.1	1723.5
	Managed forest	Mha	748.9	743.3	742.8	699.5	708.0	718.8	731.0	741.7
	Natural grassland	Mha	1490.7	1494.6	1486.8	1479.0	1471.7	1465.2	1460.7	1459.5
	Natural forest	Mha	3174.6	3164.9	3159.0	3153.0	3147.8	3140.1	3130.8	3122.4
	Other	Mha	4097.8	4097.8	4097.8	4097.8	4097.8	4097.8	4097.8	4097.8
Air Pollutant Emissions	SO_2	Tg	104.3	85.9	70.8	54.9	42.8	34.8	28.5	23.4
	NO_x	Tg	122.2	115.4	115.0	110.3	106.9	104.0	98.0	86.2
	Ammonia	Tg	48.5	49.1	54.3	58.2	59.7	61.9	62.4	61.3
	Volatile organic compounds	Tg	147.5	145.1	155.7	158.6	158.6	160.8	160.2	154.9
	Black carbon	Tg	5.0	4.5	4.3	3.9	3.5	3.2	2.8	2.4
	Organic particulates	Tg	11.4	10.4	10.4	10.0	9.3	8.7	7.9	7.0
	Carbon monoxide	Tg	581.6	579.9	632.3	655.8	665.5	680.1	679.8	659.9
Agricultural & food outputs	Crop	bil 2015 $	2416.9	2562.0	2934.2	3332.4	3572.9	3792.7	3998.3	4188.4
	Livestock	bil 2015 $	1885.6	2038.3	2337.8	2598.5	2791.6	3028.4	3216.7	3370.0
	Forest	bil 2015 $	352.4	393.0	479.4	566.8	648.8	747.1	832.0	906.3
	Food	bil 2015 $	7653.8	8150.1	9473.3	10754.9	11701.0	12829.6	13772.0	14579.8
Agricultural & food prices (2020 price = 1)	Crop			1.0	1.1	1.1	1.1	1.1	1.1	1.1
	Livestock			1.0	1.1	1.3	1.4	1.5	1.5	1.6
	Forest			1.0	1.1	1.1	1.2	1.2	1.2	1.2
	Food			1.0	1.0	1.0	1.0	1.0	1.0	1.0
Energy prices (2020 price = 1)	Coal			1.0	0.9	0.8	0.8	0.7	0.7	0.8
	Oil			1.0	1.1	1.1	1.1	1.0	1.0	0.8
	Gas			1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Electricity			1.0	1.1	1.3	1.4	1.5	1.6	1.8

Appendix

Selected results for GHG emissions and Primary Energy Use for USA and Europe (EUR) for *Paris Forever* and *Accelerated Actions* scenarios.
Extended results are available at http://globalchange.mit.edu/Outlook2021

MIT Global Change Outlook 2021 — Projection Data Tables

Region: USA **Scenario: Paris Forever**

		Units	2015	2020	2025	2030	2035	2040	2045	2050
GHG Emissions	CO$_2$ – fossil	Mt CO$_2$	5036.0	4747.0	4222.6	3806.8	3772.8	3705.1	3633.0	3612.1
	Total GHG net of Land Use	Mt CO$_2$e	6337.9	5957.9	5220.9	4731.8	4730.6	4724.5	4726.4	4728.1
	CO$_2$ – land use change	*Mt CO$_2$*	-667.1	-606.8	-545.7	-484.0	-421.8	-359.2	-296.2	-234.9
Primary Energy Use	Coal	EJ	15.5	13.6	7.4	3.9	4.3	5.1	5.3	4.9
	Oil	EJ	33.1	31.1	30.6	28.6	27.2	26.0	24.8	24.1
	Bioenergy	EJ	1.7	1.8	2.0	2.2	2.4	2.6	2.8	3.0
	Gas	EJ	28.2	28.3	31.1	32.6	33.3	32.5	32.6	34.4
	Nuclear	EJ	7.5	7.0	6.5	6.2	5.5	4.8	4.6	4.8
	Hydro	EJ	2.4	2.5	2.5	2.6	2.7	2.7	2.8	2.8
	Renewables	EJ	2.2	3.9	5.9	7.2	8.8	9.7	9.1	9.4

Region: USA **Scenario: Accelerated Actions**

		Units	2015	2020	2025	2030	2035	2040	2045	2050
GHG Emissions	CO$_2$ – fossil	Mt CO$_2$	5036.0	4747.0	3533.5	2598.8	2141.8	1646.8	1188.2	733.3
	Total GHG net of Land Use	Mt CO$_2$e	6337.9	5957.9	4588.2	3529.4	3000.0	2470.6	1941.3	1412.1
	CO$_2$ – land use change	*Mt CO$_2$*	-667.1	-606.8	-545.7	-484.0	-479.8	-393.0	-328.4	-272.5
Primary Energy Use	Coal	EJ	15.5	13.6	1.9	0.6	0.5	0.3	0.2	0.2
	Oil	EJ	33.1	31.1	29.3	25.2	22.4	19.9	15.8	10.0
	Bioenergy	EJ	1.7	1.8	2.0	2.1	2.3	2.5	2.7	2.6
	Gas	EJ	28.2	28.3	29.2	21.5	17.2	11.5	8.3	6.1
	Nuclear	EJ	7.5	7.0	6.5	6.2	5.6	5.3	5.3	5.4
	Hydro	EJ	2.4	2.5	2.6	2.7	2.8	3.0	3.1	3.3
	Renewables	EJ	2.2	3.9	5.5	10.7	16.9	23.6	25.4	27.4

Region: EUR **Scenario: Paris Forever**

		Units	2015	2020	2025	2030	2035	2040	2045	2050
GHG Emissions	CO$_2$ – fossil	Mt CO$_2$	3506.1	3112.3	3004.3	2473.5	2483.0	2478.6	2457.6	2425.8
	Total GHG net of Land Use	Mt CO$_2$e	4847.3	4758.4	4246.2	3438.2	3425.2	3408.1	3384.0	3352.9
	CO$_2$ – land use change	*Mt CO$_2$*	-99.1	-122.4	-144.2	-161.9	-175.7	-185.9	-193.4	-185.5
Primary Energy Use	Coal	EJ	11.0	7.7	5.6	3.2	3.4	2.7	2.7	2.7
	Oil	EJ	27.3	26.5	26.8	24.7	24.0	23.4	22.4	21.7
	Bioenergy	EJ	1.7	1.8	2.3	2.4	2.5	2.6	2.7	2.8
	Gas	EJ	15.1	14.2	16.0	13.7	14.2	16.1	17.1	17.6
	Nuclear	EJ	8.1	7.4	6.7	6.2	5.5	5.2	5.1	4.8
	Hydro	EJ	5.1	5.2	5.3	5.4	5.6	5.7	5.8	5.9
	Renewables	EJ	3.3	5.6	7.9	10.1	11.3	10.5	10.5	10.4

Region: EUR **Scenario: Accelerated Actions**

		Units	2015	2020	2025	2030	2035	2040	2045	2050
GHG Emissions	CO$_2$ – fossil	Mt CO$_2$	3506.1	3112.3	2972.0	1965.2	1732.0	1540.5	1150.5	671.8
	Total GHG net of Land Use	Mt CO$_2$e	4847.3	4758.4	4104.8	2852.2	2550.6	2298.3	1829.2	1239.8
	CO$_2$ – land use change	*Mt CO$_2$*	-99.1	-122.4	-144.2	-161.9	-175.7	-185.9	-193.4	-185.5
Primary Energy Use	Coal	EJ	11.0	7.7	5.5	1.3	0.8	0.6	0.4	0.2
	Oil	EJ	27.3	26.5	26.7	23.5	21.9	20.2	16.3	9.2
	Bioenergy	EJ	1.7	1.8	2.3	2.5	2.8	2.8	2.9	3.1
	Gas	EJ	15.1	14.2	16.0	10.1	8.8	7.8	6.4	5.1
	Nuclear	EJ	8.1	7.4	6.7	6.2	5.9	5.7	5.4	5.6
	Hydro	EJ	5.1	5.2	5.3	5.5	5.7	5.9	6.3	6.5
	Renewables	EJ	3.3	5.6	8.0	13.7	17.4	16.8	16.4	18.3

Appendix

Selected results for GHG emissions and Primary Energy Use for China (CHN) and India (IND) for *Paris Forever* and *Accelerated Actions* scenarios.
Extended results are available at http://globalchange.mit.edu/Outlook2021

MIT Global Change Outlook 2021

Projection Data Tables

Region: CHN **Scenario: Paris Forever**

		Units	2015	2020	2025	2030	2035	2040	2045	2050
GHG Emissions	CO_2 – fossil	Mt CO_2	9298.9	9250.1	9830.7	10411.6	9815.0	9160.5	9462.6	9769.7
	Total GHG net of Land Use	Mt CO_2e	12408.9	12376.5	12972.4	13415.0	12293.3	11455.9	11623.4	11789.5
	CO_2 – land use change	*Mt CO_2*	8.1	4.4	0.8	-2.4	-5.0	-7.3	-9.3	-10.9
Primary Energy Use	Coal	EJ	84.8	80.0	83.8	88.0	80.5	73.6	73.7	73.7
	Oil	EJ	24.8	29.2	31.7	33.4	32.9	32.3	31.5	30.8
	Bioenergy	EJ	3.7	4.1	4.7	5.0	5.1	5.3	5.2	5.4
	Gas	EJ	6.4	10.6	13.6	16.5	19.0	19.6	25.5	31.7
	Nuclear	EJ	1.2	2.3	3.3	4.7	5.4	6.1	6.1	6.1
	Hydro	EJ	9.8	11.8	12.3	13.6	15.1	16.3	16.8	17.4
	Renewables	EJ	1.9	5.2	11.4	19.0	27.7	40.0	40.3	39.7

Region: CHN **Scenario: Accelerated Actions**

		Units	2015	2020	2025	2030	2035	2040	2045	2050
GHG Emissions	CO_2 – fossil	Mt CO_2	9298.9	9250.1	9146.5	7437.4	6107.5	4886.8	3686.0	2410.9
	Total GHG net of Land Use	Mt CO_2e	12408.9	12376.5	11933.5	9813.5	7988.0	6554.9	5136.8	3627.5
	CO_2 – land use change	*Mt CO_2*	8.1	4.4	0.8	-2.4	-5.0	-7.3	-9.3	-10.9
Primary Energy Use	Coal	EJ	84.8	80.0	80.0	58.1	44.3	31.7	20.8	12.5
	Oil	EJ	24.8	29.2	31.9	34.3	32.8	32.0	31.5	30.6
	Bioenergy	EJ	3.7	4.1	4.6	4.8	4.9	5.2	5.1	5.4
	Gas	EJ	6.4	10.6	7.2	10.8	9.7	9.4	7.8	3.9
	Nuclear	EJ	1.2	2.3	3.3	4.8	5.2	5.9	6.0	6.4
	Hydro	EJ	9.8	11.8	12.4	13.9	15.6	16.9	17.7	18.3
	Renewables	EJ	1.9	5.2	12.0	27.6	50.7	65.1	67.5	77.8

Region: IND **Scenario: Paris Forever**

		Units	2015	2020	2025	2030	2035	2040	2045	2050
GHG Emissions	CO_2 – fossil	Mt CO_2	2137.8	2301.3	2583.2	2901.1	3085.0	3257.8	3425.8	3612.4
	Total GHG net of Land Use	Mt CO_2e	3484.1	3737.6	4272.4	4823.9	5205.4	5558.0	5891.6	6262.6
	CO_2 – land use change	*Mt CO_2*	-3.2	-5.6	-5.1	-6.6	-27.7	-79.3	-29.9	-24.9
Primary Energy Use	Coal	EJ	16.9	17.3	19.1	21.1	22.2	22.9	23.6	24.3
	Oil	EJ	8.1	9.6	11.1	12.7	13.7	15.0	16.2	17.6
	Bioenergy	EJ	7.6	7.6	7.6	7.6	7.5	7.5	7.2	7.0
	Gas	EJ	1.9	2.4	2.9	3.7	4.2	4.7	5.4	6.1
	Nuclear	EJ	0.3	0.4	0.6	0.9	1.0	1.9	2.3	2.7
	Hydro	EJ	1.2	1.2	1.3	1.4	1.5	1.5	1.6	1.7
	Renewables	EJ	0.4	1.0	2.8	5.8	9.9	15.5	17.6	19.5

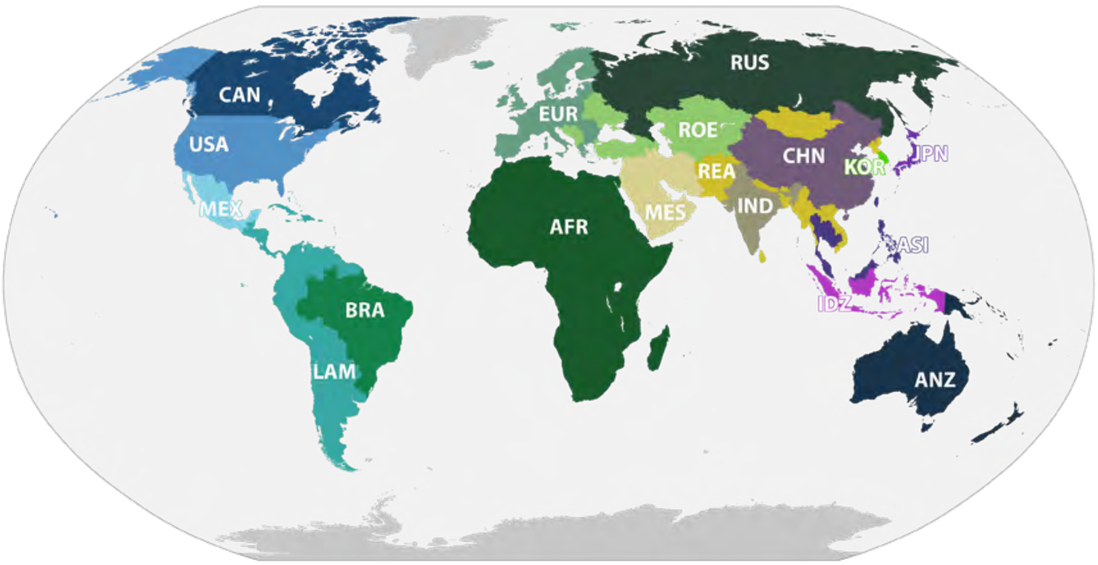
Region: IND **Scenario: Accelerated Actions**

		Units	2015	2020	2025	2030	2035	2040	2045	2050
GHG Emissions	CO_2 – fossil	Mt CO_2	2137.8	2301.3	2300.0	2265.9	1693.3	1243.8	824.8	534.2
	Total GHG net of Land Use	Mt CO_2e	3484.1	3737.6	3700.4	3734.9	3141.6	2639.0	2193.2	1778.8
	CO_2 – land use change	*Mt CO_2*	-3.2	-5.6	-5.2	-6.7	-8.0	-101.3	-32.1	-7.7
Primary Energy Use	Coal	EJ	16.9	17.3	16.3	15.4	9.9	5.7	2.9	2.0
	Oil	EJ	8.1	9.6	11.1	12.0	11.9	11.7	10.0	6.7
	Bioenergy	EJ	7.6	7.6	7.7	7.8	7.7	7.5	7.1	6.9
	Gas	EJ	1.9	2.4	2.9	3.3	3.0	2.7	2.3	2.6
	Nuclear	EJ	0.3	0.4	0.6	1.0	1.3	3.8	11.8	15.6
	Hydro	EJ	1.2	1.2	1.3	1.6	1.7	1.9	2.2	2.4
	Renewables	EJ	0.4	1.0	4.1	9.7	16.2	19.2	24.2	29.9

IGSM 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/Outlook2021



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
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
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
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
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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