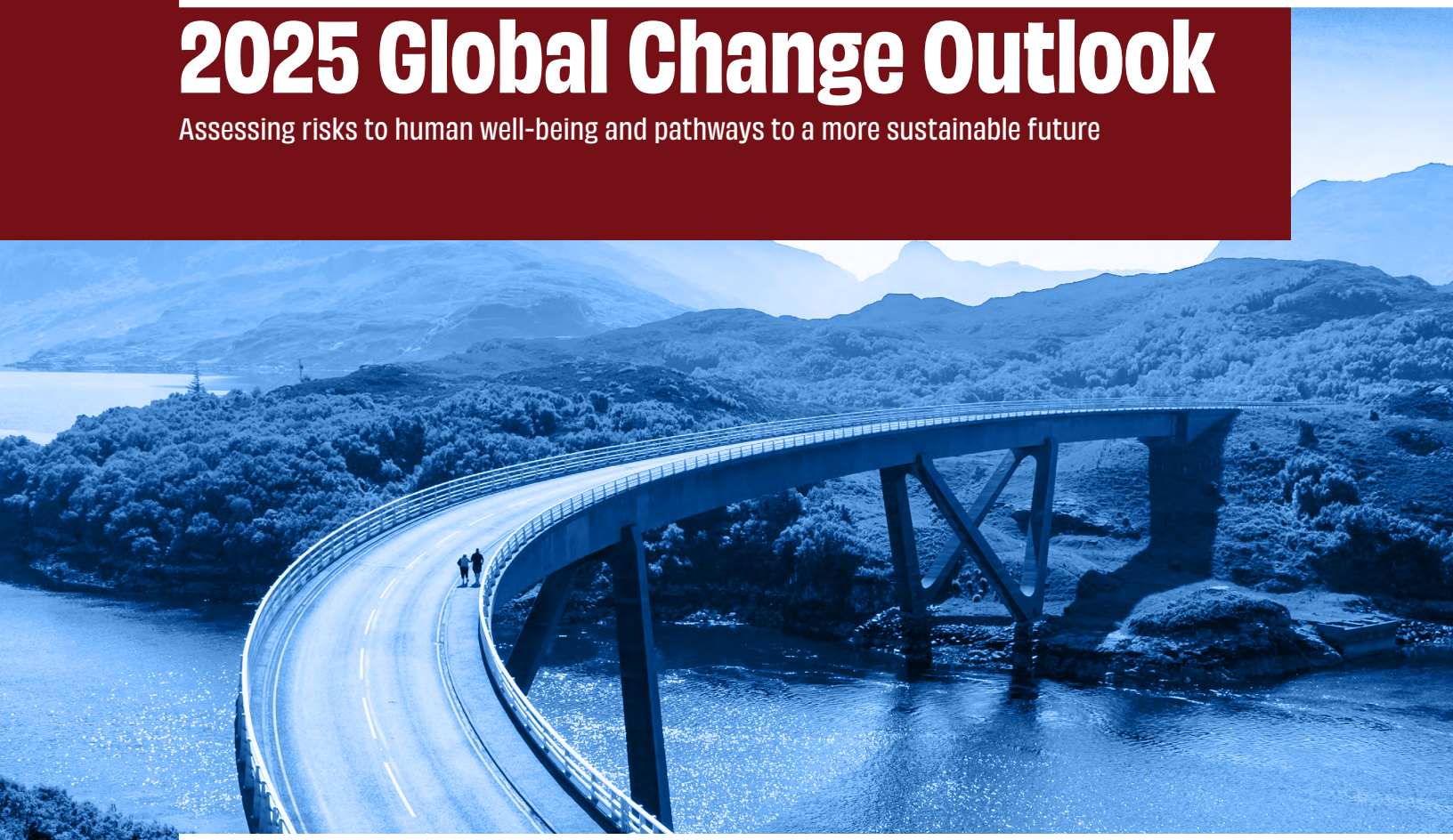
2025 Global Change Outlook

Assessing risks to human well-being and pathways to a more sustainable future



Center for Sustainability Science and Strategy

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Preparing for Tomorrow Today

The world is getting warmer, and climate extremes are becoming more intense and frequent. Arctic summer sea ice is shrinking; glaciers are retreating; and droughts and extreme heat events are becoming more frequent, and fueling more widespread wildfires. These trends, on scales from local to global, are now impacting vulnerable infrastructure, supply chains, ecosystems and human health. These impacts are likely to intensify in the coming decades.

In our 2025 Outlook we focus on two scenarios: *Current Trends*, which represents our assessment of current measures for reducing greenhouse gas emissions; and *Accelerated Actions*, which aims to limit and stabilize human-induced global climate warming to 1.5 degrees Celsius by 2100 with a 50% probability.

Our projected global climate responses under the *Current Trends* scenario indicate with near-certainty that, if present emissions trajectories continue, the world will surpass important greenhouse gas concentration thresholds and climate targets in the coming decades. Under this scenario, many regions of the world would experience more pronounced, unprecedented extreme-temperature events as human-forced climate warming intensifies.

Our projections underscore that in order to minimize risks posed by climate change, the world will need to take bolder, more collaborative actions to mitigate and adapt to it as soon as possible. In our *Accelerated Actions* scenario, we show how robust global efforts to mitigate greenhouse gas emissions can substantially improve the likelihood of achieving the global goal of keeping the global mean surface temperature rise (above preindustrial levels) below 1.5˚C. Research shows that such efforts will also be needed in order to keep today's adaptation options in play: as the global mean surface temperature rises, losses and damages to life and infrastructure will increase, pushing various natural and societal systems beyond adaptation limits.

Finally, additional policy mechanisms with more comprehensive targets will be needed to also support a cleaner environment, sustainable resources, as well as improved and equitable human health outcomes. For example, this Outlook shows that combining climate and air quality policies can help minimize air pollution and its associated health impacts. The future well-being of our planet and its inhabitants will depend on how quickly today's decision-makers advance large-scale, dramatic and sustained efforts to address multiple sustainability challenges.

We hope that our risk-benefit analysis in this report will help inform decision-makers in government, industry, academia and civil society as they confront sustainability-relevant challenges.

Noelle Selin

Director, MIT Center for Sustainability Science and Strategy

About the 2025 Outlook

A collaborative effort of the MIT Center for Sustainability Science and Strategy (CS3), the 2025 Global Change Outlook presents the Center's latest projections for the future of the Earth's energy systems, greenhouse gas emissions, and climate, as well as implications of these projections for multiple factors that affect human well-being. These include water availability and quality, biodiversity, air quality and health, agriculture, and socio-economic conditions.

Our projections in the 2025 Outlook provide an update to the 2023 Global Change Outlook which was released by the MIT Joint Program on the Science and Policy of Global Change. In 2024, MIT CS3 was launched to strengthen and expand the work of the MIT Joint Program and MIT Center for Global Change Science.

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

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 human/socio-economic systems and the Earth's response mechanisms lead to a variety of plausible futures under any proposed scenario. Through our IGSM ensemble-simulation approach, we can describe the range as well as the likelihoods of many plausible trajectories.

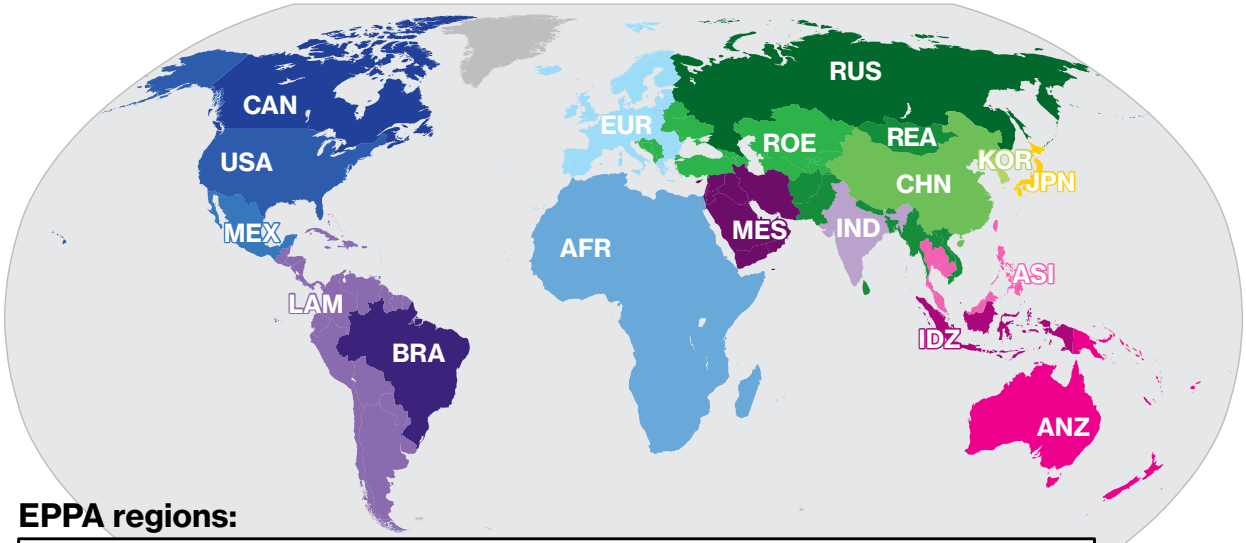
In the 2025 Outlook we focus on two scenarios. The first, which we call *Current Trends*, represents our assessment of current measures for reducing greenhouse gas emissions. While *Current Trends* represents an unprecedented global commitment to limit greenhouse gas emissions, it fails to stabilize climate, allowing global average temperatures to continue to rise. We therefore consider an additional scenario that aligns with the Paris Agreement's long-term goals. Referred to as *Accelerated Actions,* this scenario aims to limit and stabilize human-induced global climate warming to 1.5˚C by the end of this century with a 50% probability.

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

By contrasting the outcomes under these scenarios, we quantify the risks of remaining on the world's current emissions trajectory and the benefits of pursuing a much more aggressive strategy. We hope that our risk-benefit analysis will help inform decision-makers in government, industry, academia and civil society as they confront sustainability-relevant challenges.



About the 2025 Outlook



EPPA regions:

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

Fig. 1. EPPA regions

Box 1. Regional Classification Details

The projections in this Outlook are generated by the Integrated Global System Modeling (IGSM) framework and its economic component, the MIT Economic Projection and Policy Analysis (EPPA) model. Our modeling system divides the global economy into 18 regions (see **Fig. 1**).

For the reporting in this Outlook, the regions are further aggregated into three broad groups: *Developed*, *India & China* and *Rest of the World* (see **Table 1**).

A full list of the countries included in each EPPA region is provided in the Appendix.

Supplementary projection tables for 2020-2050 for all EPPA regions for the *Current Trends* and *Accelerated Actions* scenarios are available online at:

cs3.mit.edu/Outlook2025

Table 1. Outlook regional classification

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



Executive Summary

We summarize our modeled projections under two scenarios: *Current Trends*, which represents our assessment of current measures for reducing greenhouse gas emissions; and *Accelerated Actions,* a credible pathway to stabilizing the climate at a global mean surface temperature of 1.5°C above pre-industrial levels, in which countries impose more aggressive greenhouse gas emissions reduction targets. More precise scenario definitions are presented in **"Drivers of Global Change" on page 7**.

Here, we highlight global-level findings. Regional detail is provided in later sections and can be further explored through our Outlook online tables and visualization tool.

2025 Outlook Policy Scenarios

Current Trends: Current measures for reducing greenhouse gas emissions, projected indefinitely

Accelerated Actions: What may happen if regions impose more aggressive greenhouse gas emissions reduction targets

Global-level findings are highlighted here.

Regional detail is provided in later sections and can be further explored through our Outlook online tables and visualization tool.

Box 2. What's New in the 2025 Global Change Outlook

Policy scenarios

We update the policy scenarios to reflect our latest assessment of current measures for reducing greenhouse gas emissions.

Updated modeling framework

Our Integrated Global System Modeling (IGSM) framework includes a new version of the Economic Projection and Policy Analysis (EPPA) model as well as an enhanced framework that builds off the MIT Earth System Model (MESM) to provide more detailed climate outputs and climate-impact information. Key EPPA model updates include inputs related to technology costs and underlying economic data, as well as new projections of population and gross domestic product (GDP). New IGSM features include extratropical storm tracks, regional changes in extreme precipitation, and more detailed water availability and quality projections.

Data Centers

We include an explicit modeling of energy use in data centers that are needed to support artificial intelligence development.

Geopolitics and Tariffs

We consider several side cases in which the U.S. imposes tariffs on all trading partners and relaxes its greenhouse gas (GHG) emissions reduction commitments. The rest of the world either ignores these actions, or takes retaliatory measures, and/or follows the U.S. on relaxing GHG commitments.

Executive Summary

Projections

These projections are summarized in **Table 2**.

Primary Energy

Global energy consumption exhibits different patterns—it grows in *Current Trends* but declines in *Accelerated Actions* driven by improvement in energy efficiency, wider use of electricity, and demand response. Achieving long-term climate stabilization goals will require more ambitious policy measures (e.g. *Accelerated Actions*) that reduce fossil-fuel dependence and accelerate the energy transition toward low-carbon sources in all regions of the world.

Electricity

In both scenarios, global electricity consumption increases substantially, with generation from low-carbon sources becoming a dominant source of power, though *Accelerated Actions* has a much larger share of renewables. Variable renewables, such as wind and solar, are getting cheaper, but they make the electric grid more complicated, inducing integration costs and leading to higher electricity prices in *Accelerated Actions*.

Greenhouse Gas Emissions

Current policy approaches do not substantially decrease global anthropogenic greenhouse gas (GHG) emissions; without further actions, GHG emissions will start to grow again later in the century.

Projections under *Current Trends* show higher emissions than in our previous 2023 Outlook, indicating reduced action on GHG emissions mitigation in the upcoming decade. The difference, roughly equivalent to the annual emissions from Brazil or Japan, is driven by current geopolitical events.[1]

The bottom line: under *Current Trends,* the world is not on track to achieve long-term climate stabilization. Ultimately, robust government policies aligned with *Accelerated Actions* will be needed for more aggressive GHG emissions mitigation.

Climate

Curtailing global mean surface temperature rise is possible with aggressive emissions cuts: the *Accelerated Actions* scenario offers a greater than 95% chance of staying below 2°C warming. In the *Current Trends* scenario, the projected continual increase in global precipitation (which is balanced by global evaporation) indicates an intensification of the global hydrologic cycle. Yet, regional shifts in weather-related storms, extreme precipitation, as well as shortages in water resources are more variable. For example, we project that extra-tropical storm frequency and intensity will remain constant through mid-century but may increase sharply after that. Additionally, occurrences of extreme precipitation at regional scales may increase but within a large range of possible outcomes that vary across time horizons and plausible climate sensitivities.

Table 2. Major global projections in different scenarios

Category	Subcategory		*Current Trends*	*Accelerated Actions*
Primary Energy	Energy consumption	2025–2050	+17%	−16%
Electricity	Electricity use	2025–2050	+90%	+100%
	Wind & solar generation	2025–2050	+770%	+1170%
Greenhouse Gas Emissions	Anthropogenic emissions, incl. land-use change	2025–2050	−10%	−60%
Global Climate *(median of ensemble of simulations)*	Mean surface temp. change (°C relative to 1850-1900)	2050	1.79	1.62
		2100	2.74	1.56
		2150	3.72	1.5
	Precipitation change from 2025 (mm/day)	2050	+0.04	+0.03
		2075	+0.07	+0.04
		2100	+0.11	+0.04
		2150	+0.18	+0.03

1 Global GHG emissions could be 10% higher than under *Current Trends* in 2050 if regional rivalries resulting from U.S. tariff policy lead to a relaxation of climate-related regulations in regions outside the U.S. (See Box 6 on page 18.)

Implications for Sustainability

Water

Climate policies in alignment with *Accelerated Actions* can yield substantial co-benefits for water availability, particularly at local and regional scales. However, to identify strategies for sustainable water resources, additional complex factors that influence water quality must be incorporated.

Biodiversity

Achieving the 30x30 Biodiversity Goal—protecting 30% of land and oceans with high biodiversity and ecosystem functions by 2030—would lead to lower regional GDP losses under *Accelerated Actions* than it would under *Current Trends.* A policy that combines 30x30 with *Accelerated Actions* targets would require fewer subsidies to reach biodiversity targets.

Air Quality and Health

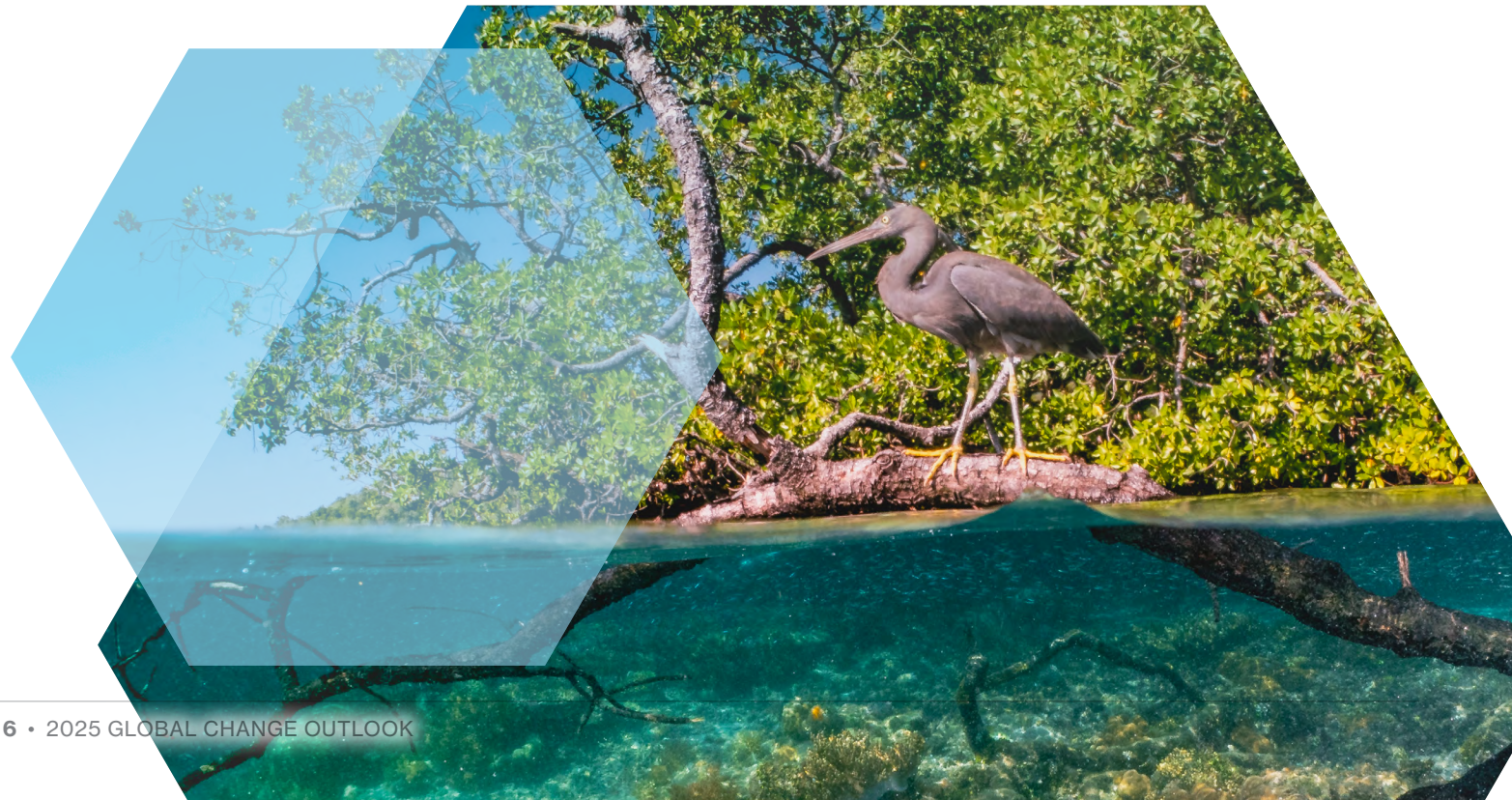
Our projections show appreciable air-quality improvements from *Accelerated Actions*-aligned policies aimed at reducing fossil fuel combustion, and how combining climate and air quality policies can reduce air pollution and associated health impacts.

Economic Impacts of Climate Change

Globally, our results suggest that planners need to think carefully about climate impacts in other regions and the resilience of global supply chains. Depending on a country's position in the global economy (its supply chains, trade patterns, relative climate vulnerability, etc.), climate impacts elsewhere can either dampen country-level economic impacts or amplify them.

Co-evolving Risks

Our new data-visualization platform, STRESS, can provide efficient, screening-level mapping of current and future climate, socio-economic and demographic-related conditions and changes. As we continue to add data and metrics from our model projections as well as supporting empirical information, the platform will provide a more comprehensive and use-inspired capability to explore co-existing and co-evolving hazards and risks. In addition to providing global mapping for many of the model outputs featured in this report, the STRESS assessment for the United States identifies focus areas for more detailed and computationally rigorous analyses.



Drivers of Global Change

Population & 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 (2024) projections from the United Nations Population Division. According to this estimate, the global population grows from 7.8 billion people in 2020 to 9.6 billion in 2050 and 10.2 billion in 2100 (**Fig. 2**). Population dynamics differ by regional grouping (see **Box 1**).

In the Developed regional group, population remains relatively stable at about 1.1 billion throughout the century. In the regional group that combines India and China, population grows from 2.8 billion in 2020 to 2.9 billion in 2050, and then declines to 2.1 billion by 2100. In 2020–2050, while India's population is projected to increase from about 1.4 billion to 1.7 billion, China's population is expected to decline from about 1.4 billion to less than 1.3 billion. Population in the Rest of the World continues to increase from 3.9 billion in 2020 to 5.5 billion in 2050, and to 7 billion in 2100. The share of the Rest of the World regional group in global population rises from 50% in 2020 to 68% in 2100.

In contrast to population, most of the globe's economic wealth in 2020 was in the Developed regional group, which accounts for almost 60% of global GDP. Collectively, India and China, the two most populous countries in the world, constitute 36% of the global population, but only about 20% of the world's total economic value. The Rest of the World regional group has 50% of global population, but its economic wealth accounts only for about 20% of global GDP. These trends of inequality persist throughout the century (**Fig. 3**).

While we project that the average annual economic growth in 2025-2100 will be higher in the India & China group (3%) and the Rest of the World group (2.9%) than in the Developed group (1.6%), the current inequality in per-capita income is reduced among world regions but not eliminated. The trends in population and GDP increase pressures on natural resources, including energy, water and land. This pressure is offset in part by technological change that increases agricultural yields and reduces energy use per unit of production activity, and other broad-scale efficiency improvements.

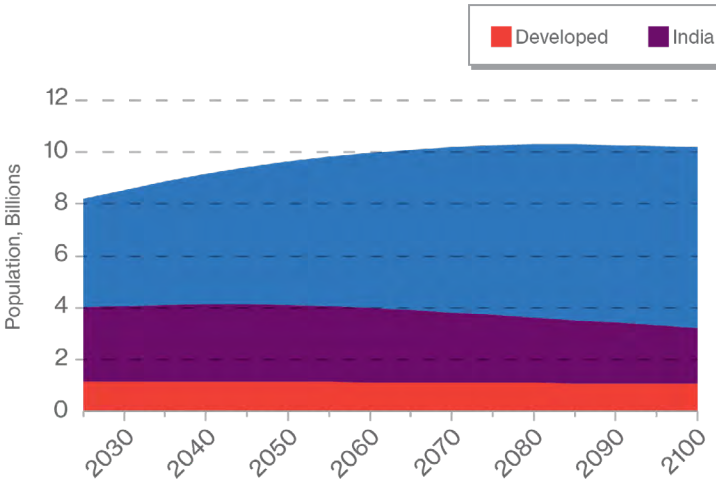


Fig. 2. World population

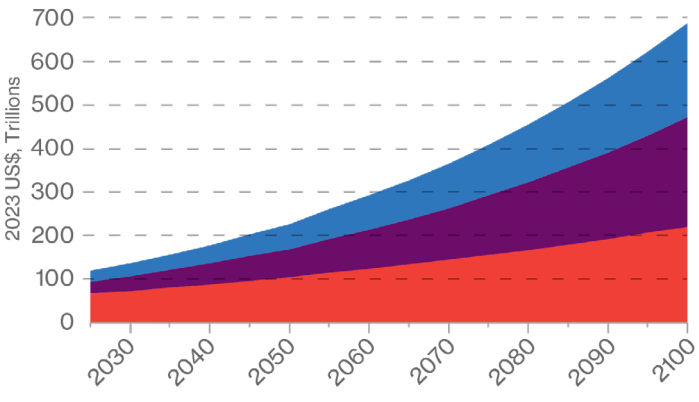


Fig. 3. World GDP

Policy Scenarios

Climate policies (including energy and land-use policies) play a key role in driving global change, as they could significantly modify the effects of population and economic growth.

Considerable interpretation is required in our modeling system to approximate the effects of policies and measures on emissions levels.

In this Outlook, we focus on the following scenarios:

- *Current Trends*, which represents our assessment of current measures for reducing greenhouse gas emissions;
- *Accelerated Actions,* a credible pathway to stabilizing the climate at a global average surface temperature of 1.5°C above pre-industrial levels, in which countries impose more aggressive greenhouse gas emissions reduction targets.

In the *Current Trends* scenario, we include our assessment of commitments under the Paris Agreement, and rely on information from Climate Action Tracker to evaluate emissions reductions. While many countries are progressing in fulfilling their Paris pledges for 2030 and submitting pledges for 2035, even more aggressive global emissions reductions are needed for reaching the goal of the Paris Agreement—"pursuing efforts to limit the temperature increase to 1.5°C."

To evaluate the impacts of aligning emissions reductions with this goal, we explore the *Accelerated Actions* scenario in which countries impose much more aggressive emissions targets than those submitted in their NDCs. The resulting emissions changes by the EPPA model regions in *Current Trends* and *Accelerated Actions* are provided in **Table 3**, where we express them as percent change in CO_2 (including fossil, industrial and land-use emissions) and GHGs relative to our projected 2025 levels.

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2025 Outlook Policy Scenarios

Current Trends: Current measures for reducing greenhouse gas emissions, projected indefinitely

Accelerated Actions: What may happen if regions impose more aggressive greenhouse gas emissions reduction targets

Box 3. Comparison to IPCC Scenarios

The Intergovernmental Panel on Climate Change (IPCC) in its latest assessment report (AR6) introduced two categories of 1.5°C-consistent scenarios, C1 and C2. Scenarios in the C1 category limit warming to 1.5°C (>50% probability) with no or limited overshoot, while the scenarios in the C2 category return warming to 1.5°C (>50%) after a high overshoot. High overshoot refers to temporarily exceeding 1.5°C global warming by 0.1-0.3°C for up to several decades. Our *Accelerated Actions* scenario is within the C2 range (see **"Temperature and Precipitation" on page 20** for temperature results).

For AR7, six groups of scenarios are proposed. Our *Accelerated Actions* scenario is consistent with a Feasible Low Scenario, aligned with the Paris Agreement.

Our research shows that achieving global net-zero emissions by 2050 is not necessarily required for climate stabilization at 1.5°C by the end of the century. However, meeting the 2050 deadline would assure the achievement of the 1.5°C target.

Drivers of Global Change • Policy Scenarios

Table 3. Emissions changes in the *Current Trends* and *Accelerated Actions* scenarios. Values relative to 2025.

Outlook Group	EPPA Region	Current Trends				Accelerated Actions			
		CO_2		GHG		CO_2		GHG	
		2035	2050	2035	2050	2035	2050	2035	2050
Developed	USA	-1%	-42%	-9%	-46%	-28%	-81%	-33%	-80%
	EUR	-10%	-31%	-21%	-39%	-37%	-78%	-47%	-80%
	CAN	1%	-40%	-7%	-42%	-34%	-87%	-36%	-85%
	JPN	-12%	-47%	-15%	-49%	-25%	-73%	-27%	-74%
	KOR	-9%	-40%	-15%	-43%	-20%	-62%	-25%	-64%
	ANZ	-4%	-28%	-10%	-29%	-21%	-62%	-24%	-58%
India & China	CHN	-6%	-31%	-4%	-24%	-42%	-82%	-36%	-68%
	IND	17%	24%	23%	40%	-22%	-56%	-4%	-16%
Rest of the World	BRA	-16%	-36%	-10%	-24%	-53%	-85%	-34%	-56%
	IDZ	5%	0%	3%	-3%	-15%	-44%	-21%	-46%
	MEX	11%	20%	8%	19%	-23%	-64%	-14%	-35%
	RUS	-4%	-8%	-7%	-15%	-33%	-63%	-31%	-59%
	ASI	9%	19%	9%	19%	-31%	-73%	-23%	-55%
	AFR	4%	21%	5%	25%	-25%	-63%	-22%	-40%
	MES	27%	53%	22%	41%	-16%	-61%	-20%	-60%
	LAM	1%	-1%	-5%	-10%	-34%	-61%	-34%	-56%
	REA	0%	1%	7%	18%	-27%	-63%	-7%	-17%
	ROE	9%	35%	6%	24%	-34%	-78%	-27%	-60%



Projections

Primary Energy

Context

Energy is a major driver of human well-being, from domestic life to economic development to societal progress. It is used directly in activities such as food preparation, transportation and home heating, and indirectly in the use of products manufactured with energy inputs. The world still heavily relies on fossil fuels for its energy needs: in 2024 about 80% of global primary (i.e., pre-processed) energy consumption was based on coal, oil and natural gas. Reducing environmentally harmful emissions from the energy sector through improvements in energy efficiency and transitioning from fossil fuels to lower-carbon energy sources (e.g., wind, solar, biomass, hydro and nuclear) is essential for realizing a sustainable future.

Key Findings

Between 2025 and 2050, global energy consumption in our *Current Trends* scenario grows from about 610 to 710 exajoules (EJ), a 17% increase (**Fig. 4a**). The share of low-carbon energy sources grows from about 20% to 33%, led by variable renewable energy (wind and solar), which increases almost nine-fold. Meanwhile, nuclear power grows by 60%, hydropower by 20%, and bioenergy by 20%. While these increases in low-carbon energy move the global energy system toward greater sustainability, the speed of transition is not ambitious enough. Coal consumption declines by 27%, but liquids (oil and first-generation biofuels) consumption stays roughly flat, and natural gas consumption grows by about 15%.

Climate stabilization goals will require more ambitious policy measures to accelerate the energy transition to low-carbon sources.

Our *Accelerated Actions* scenario shows a much different trajectory over the same period (**Fig. 4b**). Global energy consumption declines after 2025 to about 510 EJ in 2050, with price- and policy-driven energy-efficiency measures playing a substantial role in reducing annual consumption. The share of low-carbon energy sources grows from 20% in 2020 to almost 60% in 2050, much faster than in *Current Trends*, with wind and solar increasing almost 13-fold. Nuclear power, hydropower and bioenergy grow by 80%, 25% and 35%, respectively. In contrast, all fossil fuel consumption declines: coal by 86%, natural gas by 64% and oil by 30%.

Energy profile trajectories differ in the Developed, India & China, and Rest of the World regional groups. In *Current Trends*, energy consumption in the Developed region peaks in 2035 and then slightly declines by 2050 (**Fig. 5a**), largely due to emissions mitigation policies and

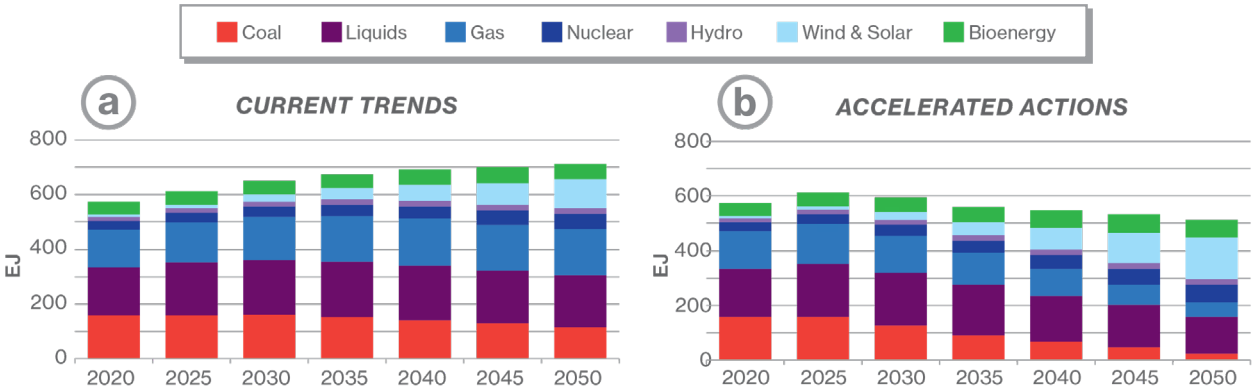


Fig. 4. Global primary energy consumption (exajoules) in the *Current Trends* (a) and *Accelerated Actions* (b) scenarios

Projections • Primary Energy

electrification. However, energy consumption grows by 15% between 2025 and 2050 in India & China (**Fig. 5b**) and by 35% in the Rest of the World (**Fig. 5c**). The prominence of different energy sources varies by region.

In *Accelerated Actions* (**Fig. 6**), total primary energy consumption declines from 2025 to 2050 in all three regional groups: by 20% in the Developed and India & China groups, and by 10% in the Rest of the World. All three groups experience a dramatic global reduction in coal use and substantial declines in natural gas and oil consumption, coupled with explosive growth in wind and solar energy (10-fold in the Developed group, 12-fold in India & China and 25-fold in the Rest of the World).

Implications

The current trajectory for global energy does not substantially decrease reliance on fossil fuels. Achieving a sustainable future aligned with long-term climate stabilization goals will require more ambitious policy measures (e.g. *Accelerated Actions*) that reduce fossil-fuel dependence and accelerate the energy transition toward low-carbon sources in all regions of the world.

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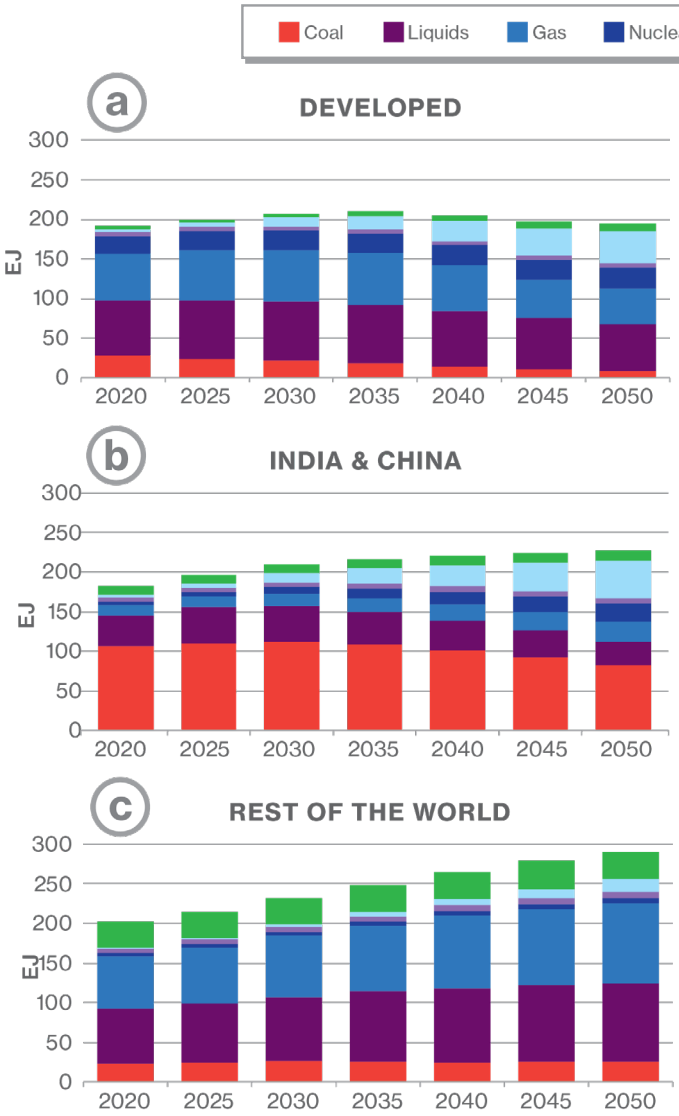


Fig. 5. Primary Energy Consumption (exajoules) in *Current Trends* by regional group: Developed (a), India & China (b), Rest of the World (c)

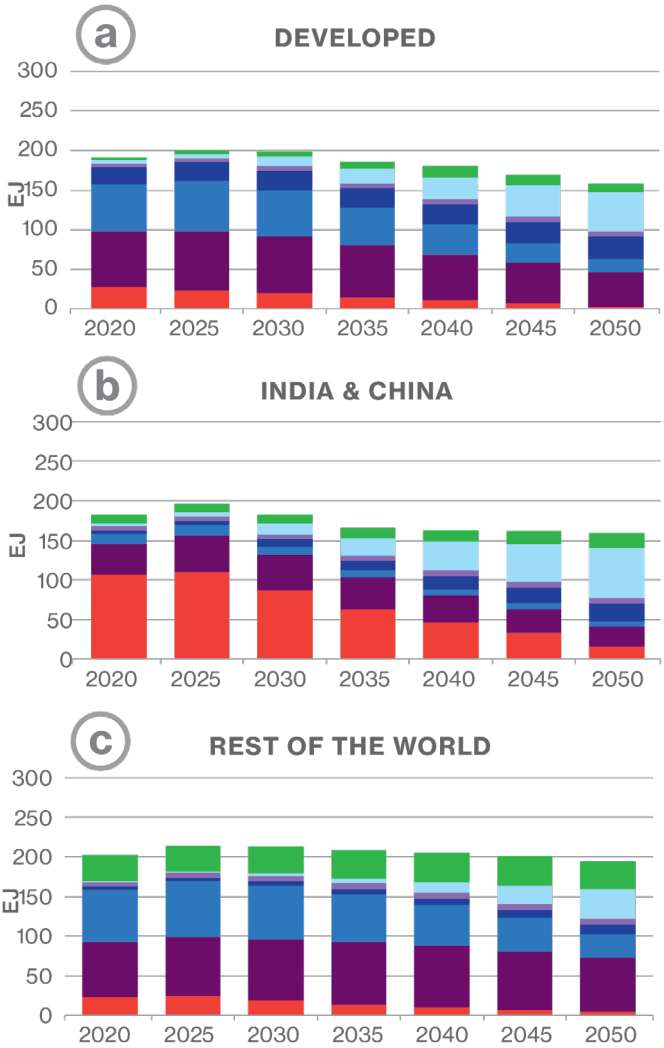


Fig. 6. Primary Energy Consumption (exajoules) in *Accelerated Actions* by regional group: Developed (a), India & China (b), Rest of the World (c)

Electricity

Context

A strategy of coupling electrification with decarbonizing electricity can deliver substantial progress toward a low-carbon economy. But intermittency challenges for variable renewables (wind and solar) will need to be resolved to ensure electric grid stability amid increasing electricity demand for multiple uses, including industrial processes, transportation, space cooling and artificial intelligence (see **Box 4. "Energy for Data Centers" on page 14**).

Key Findings

We project extensive growth in global electricity production and consumption. From 2025 to 2050, electricity use grows by almost 90% in the *Current Trends* scenario (**Fig. 7a**). Compared to primary energy growth of 17% over this period, electricity grows much faster, resulting in a continuing electrification of the global economy. We project substantial switching from coal to natural gas generation, with coal decreasing by 40% and natural gas increasing by 20%. The fastest growth comes from variable renewables, with an almost nine-fold increase. The combined share of low-carbon sources of electricity (wind, solar, nuclear, hydro, biomass) increases from 40% to about 73%.

In the *Accelerated Actions* scenario (**Fig. 7b**), global electricity production grows even faster, rising by about 100% between 2025 and 2050. More ambitious climate policies lead to a larger growth in variable renewables, which increase almost 13-fold. Other low-carbon sources also grow. As a result, global power generation is largely decarbonized by mid-century, with low-carbon sources contributing more than 90% to total electricity production in 2050.

Low-carbon power generation becomes dominant in both scenarios.

Among the major regional groups in *Current Trends* (**Fig. 8**), the India & China group shows the fastest growth in electricity production (about 110%), followed by the Rest of the World (85%) and the Developed group (70%). Coal generation declines in all regions, led by the Developed group. While renewables grow in all regions, natural gas remains a sizeable option in this scenario. In *Accelerated Actions* (**Fig. 9**), the general trends are similar, but with a faster growth in low-carbon options and decline in fossil-based options, and a smaller role for natural gas by mid-century.

Implications

Electricity generation from low-carbon sources becomes a dominant source of power in both of our scenarios, but it comes with an increase in electricity prices. While price increases differ by region, the average global electricity price rises from 2025 to 2050 by 40% in *Current Trends* and by 80% in *Accelerated Actions*. Price increases

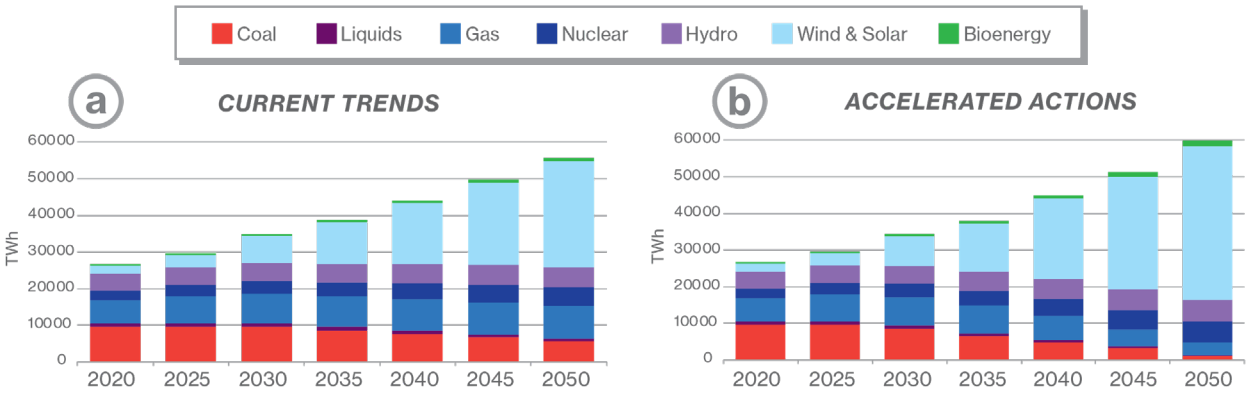


Fig. 7. Global electricity production (terawatt-hour, TWh) in the *Current Trends* (a) and *Accelerated Actions* (b) scenarios

Projections • Electricity

are mostly driven by policy requirements to include more low-carbon generation options. Variable renewables, such as wind and solar, are getting cheaper, but they make the electric grid more complicated, inducing integration costs[1]. Also, in many countries, old generation plants are now producing at prices that are too low to recover the full cost of replacing these plants. 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 back-up capacity and power storage options.

Author: Sergey Paltsev

Variable renewables are getting cheaper, but they complicate the electric grid—inducing integration costs.

1 Gurgel, A., *et al.* (2023). Variable renewable energy deployment in low-emission scenarios: the role of technology cost and value. *Applied Energy*, 344, 121119 (doi: 10.1016/j.apenergy.2023.121119).

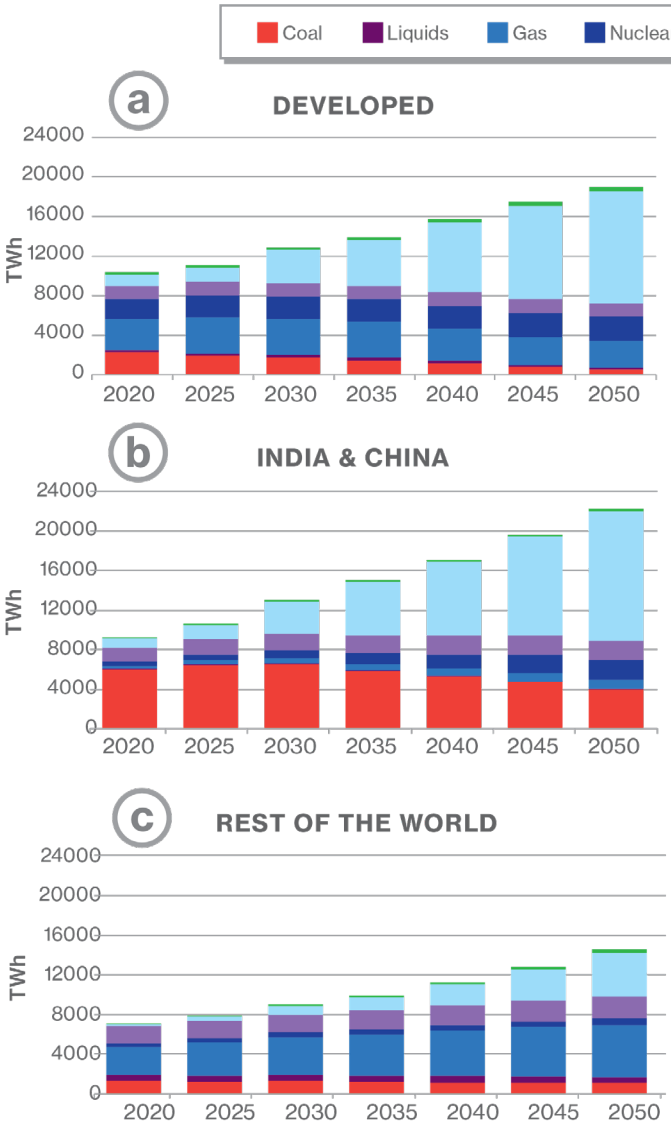


Fig. 8. Electricity production (terawatt-hour, TWh) in the *Current Trends* scenario by regional group: Developed (a), India & China (b), Rest of the World (c)

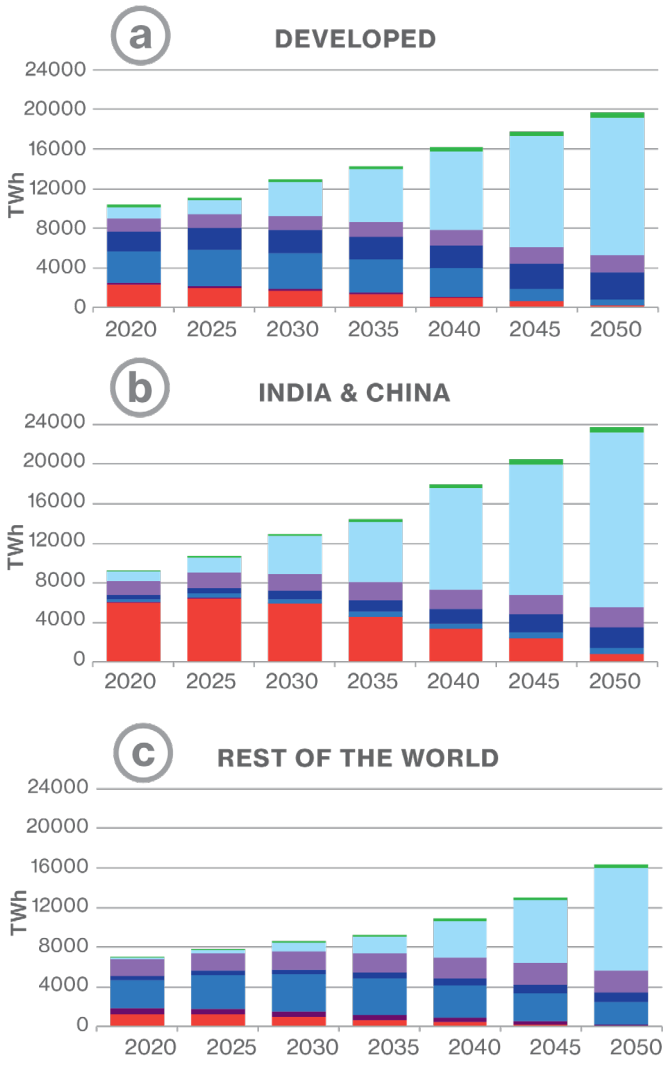


Fig. 9. Electricity production (terawatt-hour, TWh) in the *Accelerated Actions* scenario by regional group: Developed (a), India & China (b), Rest of the World (c)

Box 4. Energy for Data Centers

To support artificial intelligence (AI) training and deployment, a growing number of highly energy-intensive data centers are being built. In 2024 they accounted for about 1.5% of global electricity consumption, and more than 4% in the U.S. Rising demands for electricity in data centers pose substantial challenges for energy deployment and emissions mitigation.

Under our *Current Trends* scenario, we project that global electricity needs for data centers will increase 3.7-fold in the coming decade (**Table 4**). By 2050, electricity use in data centers will increase further and reach about 3,750 terawatt-hours (TWh), equivalent to the total electricity consumption in Europe in 2023. From 2025 to 2050, the U.S. share of global data centers will remain at about 40%, and China's share will rise from about 30% to 40%. Our results show the projected dominance of these two countries in AI development, driven by massive investments, access to cheap electricity, and geopolitical competition.

We project that data centers' installed capacity in the U.S. will reach about 100 gigawatts (GW) by 2030, with about 14 GW added each year between 2030 and 2050. As a result, by 2050 about 17% of all U.S. electricity will be consumed in data centers that power the computing capacity required for AI. The corresponding number for China is 8%, and about 7% at the global level.

Because data centers currently have limited ability to shift their workloads to different times of the day, they require a stable power supply. This is typically provided by natural gas, nuclear or other baseload electricity sources that do not vary with wind and sun availability. Hence, emissions impacts can be substantial if power supply stability or data center operational flexibility are not addressed in the future. While today's AI companies are willing to pay premium prices for power, access to cheap electricity will become critical—particularly for other regions beyond the U.S. and China that aspire to be competitive in the AI race. Current increases in electricity demand for U.S. data centers are mostly powered by natural gas, which affects the costs of new natural gas-based generation globally. This could negatively impact regions with substantial shares of coal-based generation that plan to switch to natural gas and reduce emissions. If they decide to keep coal generation longer than planned, it will worsen environmental impacts. Hence, there is a critical need to develop solutions to power data centers that are both reliable and sustainable.

Author: Sergey Paltsev

Table 4. Global electricity consumption in data centers (TWh), and shares of USA and China in global consumption

	2025	2030	2035	2040	2045	2050
World (TWh)	447	916	1643	2447	3203	3752
USA (share)	41%	43%	43%	43%	42%	41%
China (share)	27%	30%	33%	36%	37%	38%

Projections • Africa

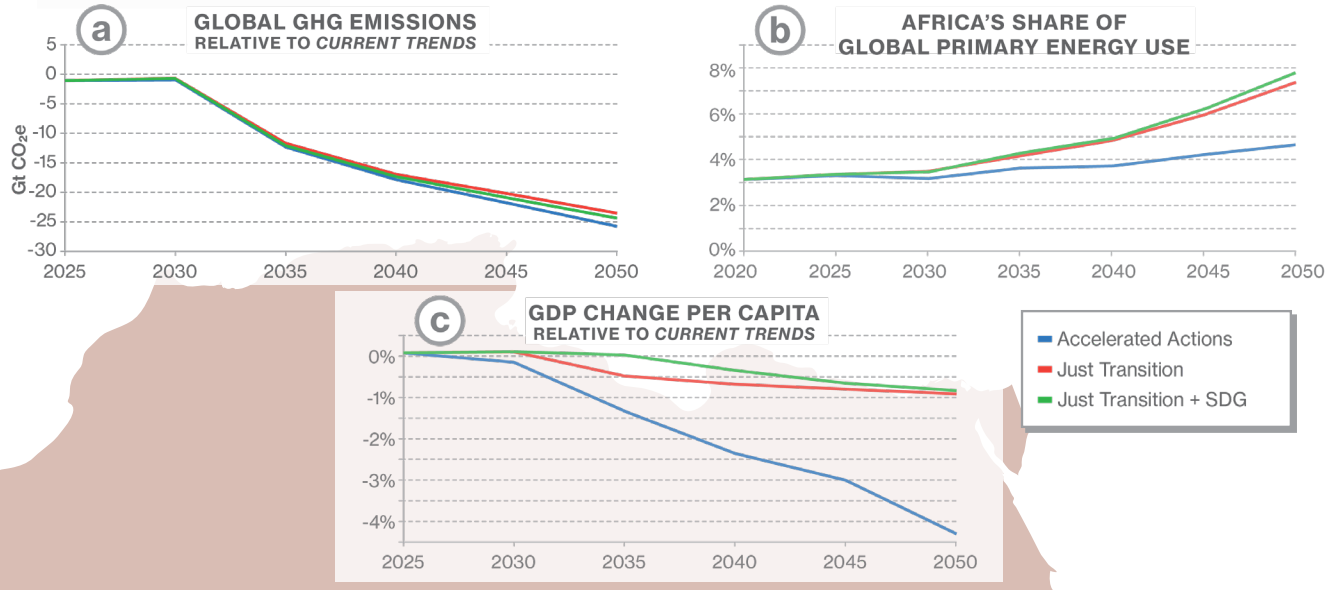


Fig. 10. (a) Changes in global GHG emissions relative to *Current Trends*, (b) Africa's primary energy use (excluding traditional biomass) as a share of global primary energy use, and (c) % change in Africa's GDP per capita relative to *Current Trends* in three alternative scenarios, detailed in the text.

Box 5. Sustainable Development and Energy Transition in Africa

Africa faces several sustainable development challenges, including poverty, persistent gaps in income per capita, energy access and health issues. In particular, more than 600 million people live without access to electricity and nearly 1 billion lack access to clean cooking supplies[1]. These challenges are exacerbated by a rapidly growing population, which is expected to double by 2050 and triple by 2100. At the same time, the continent has a rich and diverse distribution of natural resources, from natural renewable resources and large biodiverse ecosystems to non-renewable resources such as critical minerals (30% of the world's proven reserves), oil (over 125 billion barrels) and gas (over 488 trillion cubic feet)[2]. It also has the second largest natural tropical forests and carbon sinks in the world and five of the top ten countries with the greatest solar energy potentials in the world. It is essential for Africa to manage these resources in alignment with economic, social and environmental sustainable development goals.

Highly vulnerable to the physical impacts of climate change[3], Africa also faces risks from a low-carbon transition. The continent contributes only 3% of global emissions[1], but depends heavily on fossil fuels, which comprise about 57% of its total energy supply and 75% of its electricity generation. On average, 25% of government revenues in Sub-Saharan Africa come from fossil fuel exports (over 80% in some countries). Much of its fossil infrastructure has been developed with foreign finance. A low-carbon transition creates the risk of stranded assets, lower export revenues and higher domestic energy costs.

It is therefore critical to explore just transition scenarios for Africa, which we have done with our MIT Economic Projection and Policy Analysis (EPPA) model (**Fig. 10**). Exempting Africa from curbing emissions through mid-century (the "Just Transition" scenario) could reduce the continent's energy access gap with negligible impact on global greenhouse gas emissions compared to the *Accelerated Actions* scenario. Protecting natural forests while strategically utilizing natural gas resources (the "Just Transition + SDG" scenario) could facilitate the replacement of biomass with cooking gas, bringing health benefits to households while protecting ecosystems and reducing deforestation emissions enough to offset the emissions from increased natural gas use. Both just transition scenarios increase Africa's primary energy use and reduce the impact of global climate policy on the continent's economic growth. Strategies such as these can enable sustainable development in Africa, enhancing energy access, enabling manufacturing development and economic growth, creating jobs for the growing young workforce, and reducing poverty, all while still allowing for global emissions reductions.

Author: Jennifer Morris and Angelo Gurgel

1 IEA [International Energy Agency] (2025). https://www.iea.org/regions/africa

2 African Export-Import Bank (2020). *Industry Outlook: Oil & Gas Q1 2020*. (Cairo: African Export-Import Bank, PDF, 28 pp., accessed Dec 5 2025 https://media.afreximbank.com/afrexim/Industry-Outlook_OilGas_2020_Q1.pdf

3 Fonjong, L., *et al.* (2024). Climate change in Africa: Impacts, adaptation, and policy responses. *Global Environmental Change*, 89, 102912 (doi:10.1016/j.gloenvcha.2024.102912).

Greenhouse Gas Emissions

Context

Anthropogenic greenhouse gas (GHG) emissions result from a wide range of industrial, agricultural and other human activities. Carbon dioxide (CO_2), generated primarily from the combustion of fossil fuels, is the largest source of global anthropogenic GHG emissions. The second largest source, methane (CH_4), is mainly produced by agriculture (especially livestock and rice production), but also by fossil energy production and distribution, and waste management. The third largest source, nitrous oxide (N_2O), arises primarily from nitrogen fertilizer but also from fuel combustion, waste water and industrial processes. Smaller sources of GHG emissions include industrial and land-use sources of CO_2 and fluorocarbons (PFCs, HFCs, SF_6).

Current policy approaches do not substantially decrease global GHG emissions, which will start to grow again later in the century.

Key Findings

Global GHG emissions in the *Current Trends* scenario are projected to initially peak in 2030 at about 53 gigatonnes of CO_2-equivalent (Gt CO_2e), and then gradually decrease to about 47 Gt CO_2e in 2050 (**Fig. 11a**) due to actions by countries with more stringent emissions mitigation policies. From 2025 to 2050, GHG emissions in the Developed region decline by 43% and in the India & China region by 11%. However, this reduction is counterbalanced by an increase in the Rest of the World, where emissions grow by 11% due to negligible mitigation policies (**Fig. 11b**).

In the *Accelerated Actions* scenario, more aggressive policies lead to a mid-century reduction in global GHG emissions by about 60% relative to 2025 (**Fig. 12a**), with declining emissions in all regions (**Fig. 12b**). In the Developed regional group they decrease by about 80%, in

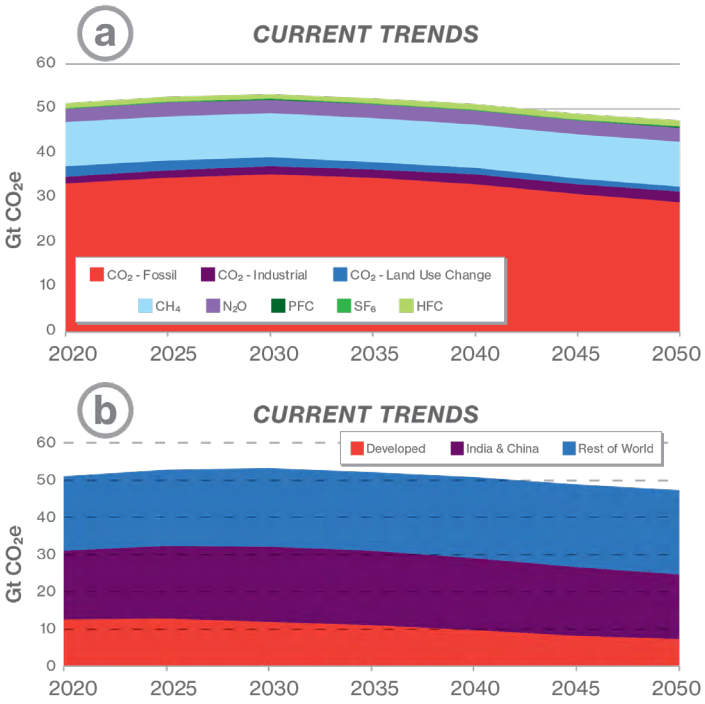


Fig. 11. Global annual GHG emissions in the *Current Trends* scenario by gas (a) and regional group (b)

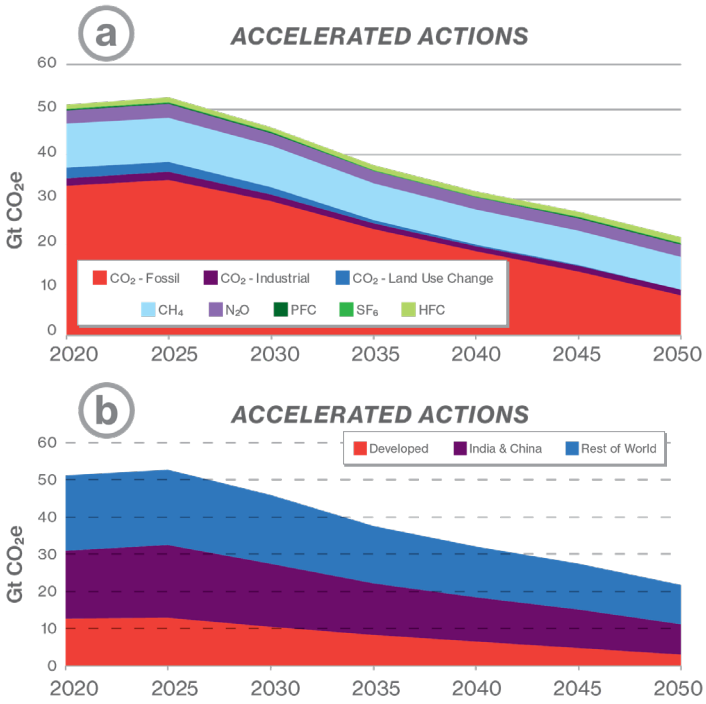


Fig. 12. Global annual GHG emissions in the *Accelerated Actions* scenario by gas (a) and regional group (b)

Projections • Greenhouse Gas Emissions

India & China by about 60%, and in the Rest of the World by about 50%. Ambitious changes in current policy approaches will be needed to achieve emissions reductions of this magnitude.

We also extend our projections to 2150 (**Fig. 13**) based on the scenario descriptions provided in **"Drivers of Global Change" on page 7**. While global CO_2 emissions in *Current Trends* remain relatively flat at about 35 Gt CO_2e per year, reflecting mild policies on energy and industrial emissions, our global GHG emissions projection shows a gradual increase in agriculture-related CH_4 and N_2O due to global population and GDP growth.

In *Accelerated Actions,* global GHG emissions continue to decline until the end of the century, reaching about 5 Gt CO_2e per year. At that time CH_4 and N_2O are still not fully eliminated because of agriculture-related activities. Negative CO_2 emissions in the second half of the 21st century (driven by carbon removal technologies) enable a slight increase in emissions that stay flat at about 1 Gt CO_2e throughout the 22nd century.

Implications

Current policy approaches do not substantially decrease global anthropogenic greenhouse gas (GHG) emissions; without further actions, GHG emissions will start to grow again later in the century. Projections under *Current Trends* show higher emissions than in our previous 2023 Outlook, indicating reduced action on GHG emissions mitigation in the upcoming decade driven by current geopolitical events. While the 2023 Outlook projected that global GHG emissions in 2030 would grow by 0.8 Gt CO_2e relative to 2020, our current Outlook projects they will grow by 2.1 Gt CO_2e. The difference—1.3 Gt CO_2e—is roughly equivalent to the annual emissions from Brazil or Japan, and remains about the same in 2035. The bottom line is that the world is not on track to achieve long-term climate stabilization. Ultimately, robust government policies will be needed for more aggressive GHG emissions mitigation.

Author: Sergey Paltsev

*Bottom line: The world is not on track to achieve long-term climate stabilization. Robust **Accelerated Actions** policies are needed.*

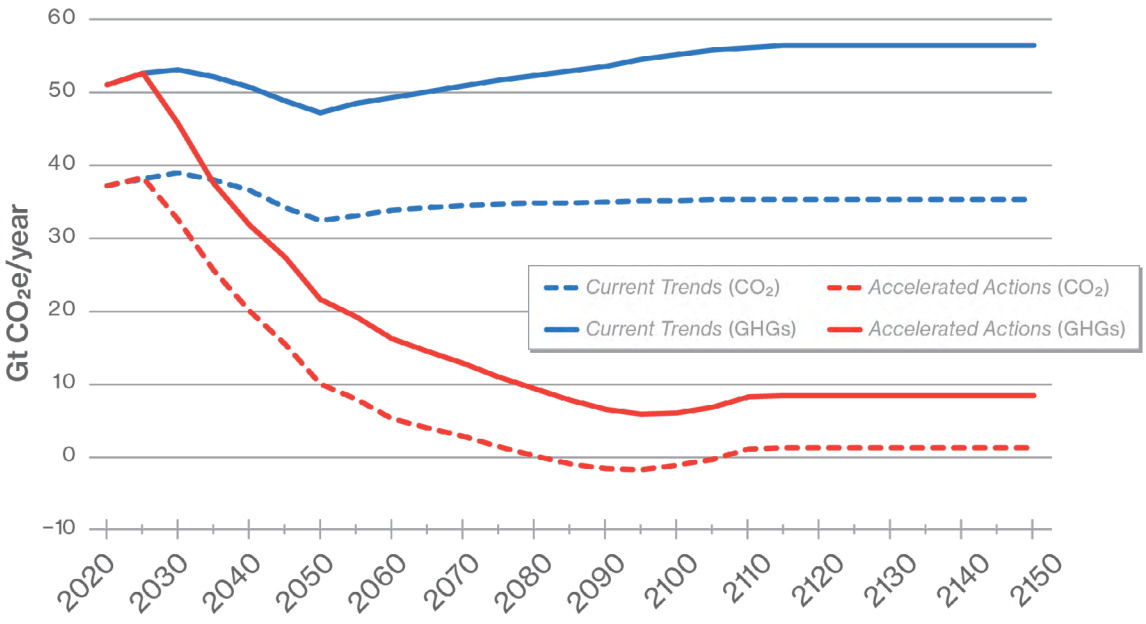


Fig. 13. Global annual GHG emissions up to 2150

Box 6. Tariffs and Regional Rivalries

The massive escalation of geopolitical threats and imposition of U.S. tariffs have created substantial uncertainty for the global economy. Because tariffs affect the costs of imported goods, industries that rely on international supply chains could be considerably affected. While domestic production and supply chains may benefit, trade barriers could lead to higher prices with resulting negative impacts on disposable incomes and economic growth. These impacts could further affect trade patterns, technology deployment and emissions related to different economic activities. Levels of U.S. tariffs and possible retaliation measures against them remain ambiguous. Tariff negotiations are ongoing, and many tariffs have been amended or delayed after being announced. It is also unclear how long tariffs and other retaliatory measures will last. In any case, regional rivalries are expected to impact the world economy in coming years.

We explored a set of *Regional Rivalries* scenarios, in which the U.S. imposes tariffs on all trading partners and relaxes its greenhouse gas (GHG) emissions reduction commitments. The rest of the world either ignores these actions, or takes retaliatory measures and/or follows the U.S. on relaxing their GHG commitments.

In the case where all U.S. tariffs are unilaterally increased by 50% for 2025-2050 and other regions do not take any retaliatory actions, global GDP does not change substantially from our *Current Trends* scenario, but annual U.S. GDP is about 0.1% lower relative to *Current Trends* in 2030-2050. If all other countries impose reciprocal tariffs, global GDP declines by 0.1% and GHG emissions decrease by 0.2% due to reduced economic activity. In both of these cases, we assume that all countries still follow their policies as specified in *Current Trends*, hence the impact on global emissions is small.

However, removal of GHG regulations in the U.S. (combined with tariffs) leads to increased U.S fossil fuel consumption and GHG emissions. In comparison to our projections in *Current Trends*, U.S. GHG emissions could be about 10% larger in 2040 (5,600 Mt CO_2e vs. 5,180 Mt CO_2e), and 30% larger in 2050 (4,700 Mt CO_2e vs. 3,490 Mt CO_2e). This setting results in an increase in global GHG emissions by 2.7% in 2050 relative to *Current Trends*. However, if regional rivalries lead to a relaxation of climate-related regulations in regions outside the U.S., then by 2050 global GHG emissions could be 10% higher than they would be under *Current Trends*.

Ultimately, the impact of U.S. tariffs will depend on other countries' reactions. If they maintain current climate policy strategies, then global GHG emissions will not change substantially from trajectories projected under *Current Trends*. However, if regional rivalries lead to a relaxation of climate-related regulations in regions outside the U.S., then global GHG emissions could be much higher. This would make it even harder to achieve the results described in our *Accelerated Actions* scenario. Overall, the tariffs will lead to uncertainty and slower global economic growth. However, the absence of strong climate actions from the U.S. could create opportunities for other regions (e.g., the EU, China and India) to become the global leaders and beneficiaries from low-carbon energy deployment.

Author: Sergey Paltsev

Projections • Plastic Use

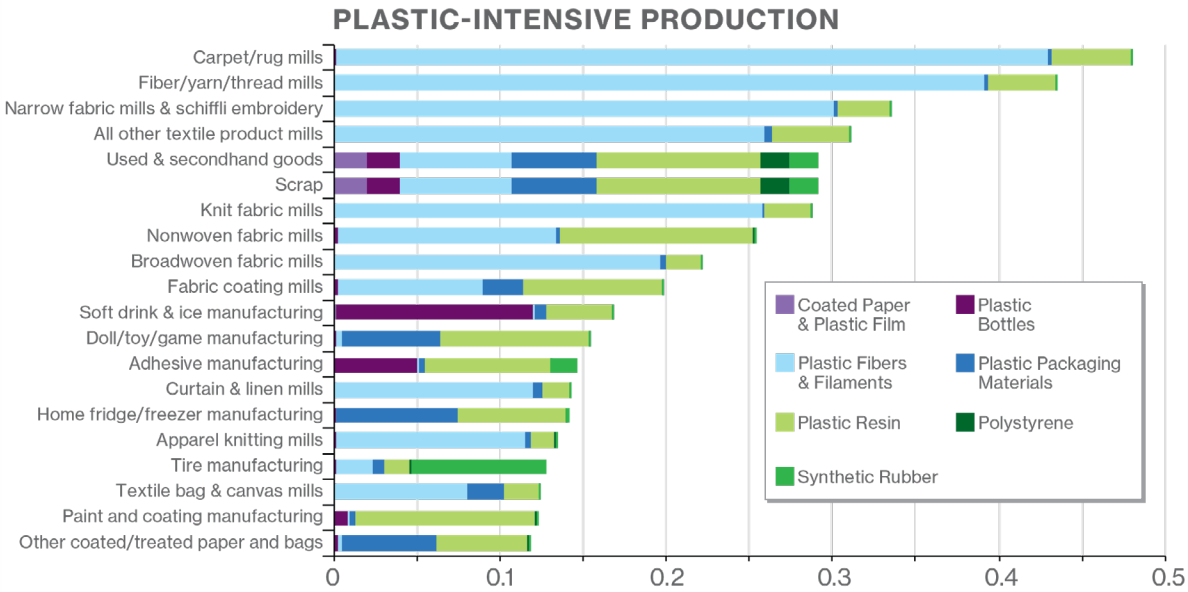


Fig. 14. Plastic intensity by industry and polluting plastic type in the US (20 most plastic intensive industries).[3]

Box 7. Plastic Use and Policy Analysis

Plastic use and its associated environmental impacts have come under considerable scrutiny in recent years, leading to the introduction of new policies in several world regions[1]. Meanwhile, ongoing United Nations negotiations for a legally binding deal to end plastic pollution have not yet reached a consensus among member states[2]. Any viable solution to plastic pollution will require accurate and detailed data on plastic use by industries.

Recently, we used economic data to estimate the plastic intensity (dollars of plastic used for every dollar of output) of industries in the U.S.[3] We found that clothing and fabric manufacturing are highly plastic intensive, especially for fibers and filaments. These industries represent 55% of the top 20 polluting plastic-intensive industries in the U.S. (see **Fig. 14**). This is particularly concerning, as clothing and textiles made with plastic release microplastics into waterways every time they are washed[4,5,6,7].

A global effort to end plastic pollution would require either the addition of effective plastic filtration systems to wastewater systems, or the production of clothing without plastics. In a subsequent study, we used a global economic model similar to the MIT Economic Projection and Policy Analysis (EPPA) model to explore potential policies which could incentivize the production of clothing that is plastic-free and made using natural chemicals.[8] Our results suggest that plastic and synthetic chemical-free clothing production favors more traditional plastic-free agricultural alternatives such as cotton and natural rubber at the expense of land use for food-based agriculture.

Our research shows how economic data and modeling can help decision-makers identify and reduce plastic pollution. MIT CS3 could build on this work by using either the U.S. Regional Energy Policy (USREP) or EPPA model to explore the potential impacts of U.S. or global plastic policies on consumption and production. Environmental models could then use this data to explore how changes in plastic use could impact water quality and global emissions.

Authors: Dominic White and Niven Winchester

1 Howard, B.C., *et al.* (2019). *A running list of action on plastic pollution*. National Geographic Society. https://www.nationalgeographic.com/environment/article/ocean-plastic-pollution-solutions [Accessed 18 Sept 2025]

2 UN. (2025). *Plastic pollution treaty talks adjourn, but countries want to 'remain at the table': UNEP chief*. UN News, New York. https://news.un.org/en/story/2025/08/1165658 [Accessed 18 Sept 2025]

3 White, D. & Winchester, N. (2023). The plastic intensity of industries in the USA: the devil wears plastic. *Environ Model Assess, 28*, 15–28 (doi:10.1007/s10666-022-09848-z).

4 Browne, M.A., *et al.* (2011). Accumulation of microplastic on shorelines worldwide: sources and sinks. *Environ Sci Technol, 45*(21), 9175–9179 (doi:10.1021/es201811s).

5 Cai, Y., *et al.* (2020). Systematic study of microplastic fiber release from 12 different polyester textiles during washing. *Environ Sci Technol*, 54(8), 4847–4855 (doi:10.1021/acs.est.9b07395).

6 Choi, S., *et al.* (2021). Analysis of microplastics released from plain woven classified by yarn types during washing and drying. *Polymers, 13*(7), 2988 (doi:10.3390/polym13172988).

7 Dalla Fontana, G., *et al.* (2020). Assessment of microplastics release from polyester fabrics: the impact of different washing conditions. *Environ Poll, 264*, 113960 (doi:10.1016/j.envpol.2020.113960).

8 White, D. & Winchester, N. (2024). Making a material difference: The impacts of a change to plastic-free clothing. *Aus J of Ag & Res Econ*, *69*(1), 200-231 (doi:10.1111/1467-8489.12599).

Temperature and Precipitation

Context

The extent of human-driven climate change is commonly measured by changes in global mean surface temperature (GMST), which averages land temperatures at two meters above ground with sea-surface temperatures. GMST rise is primarily driven by heat-trapping emissions, and can also be affected by land-use changes as well as other natural and anthropogenic factors. Consequently, international climate targets are set based on GMST changes, and global efforts have often been evaluated by the likelihood of meeting these targets. Further, the potential impacts and adaptation implications of human-forced temperature change are inferred through the global lens of precipitation change.

Nevertheless, the Earth's climate system is complex, and this complexity leads to deviations in model projections when details in the forcings (i.e., emissions) and responses (i.e., clouds, oceans, air chemistry, and hydrology) are even slightly lacking. We use the IGSM framework to model these complexities and represent uncertainties. Our ensemble-simulation approach (running many plausible combinations of model assumptions) can determine the likelihoods of global outcomes and effectiveness of actions toward achieving a climate target.

With aggressive emissions cuts, keeping the increase in global mean surface temperature to below 2˚C becomes highly likely.

Key Findings

Among the most recognized climate targets are to keep GMST change (from pre-industrial conditions) at or below 1.5˚C or 2˚C by the end of this century (yellow band in **Fig. 15**). We find that nearly all the IGSM ensemble's projections exceed 1.5˚C warming by 2045 and 2˚C warming by 2080 in the *Current Trends* scenario. By 2100, under *Current Trends*, GMST warming is likely (i.e., middle of the ensemble, or median result) to reach nearly 2.75˚C—and almost certain to exceed 2˚C. By the mid-22nd century, GMST is projected with very high likelihood (i.e., greater than 95% chance) to warm by at least 3˚C and likely by 3.75˚C (given the 3.72˚C median warming result). In contrast, the *Accelerated Actions* scenario results in significant reductions to GMST warming. The likelihood that GMST warming exceeds 2˚C under *Accelerated Actions* is low, with about a 5% chance through the 2060s and 2070s. There is, however, a period of high likelihood (i.e., greater than 75% chance) to overshoot the 1.5˚C target that spans from 2040-2080. In *Accelerated Actions*, there is only a small

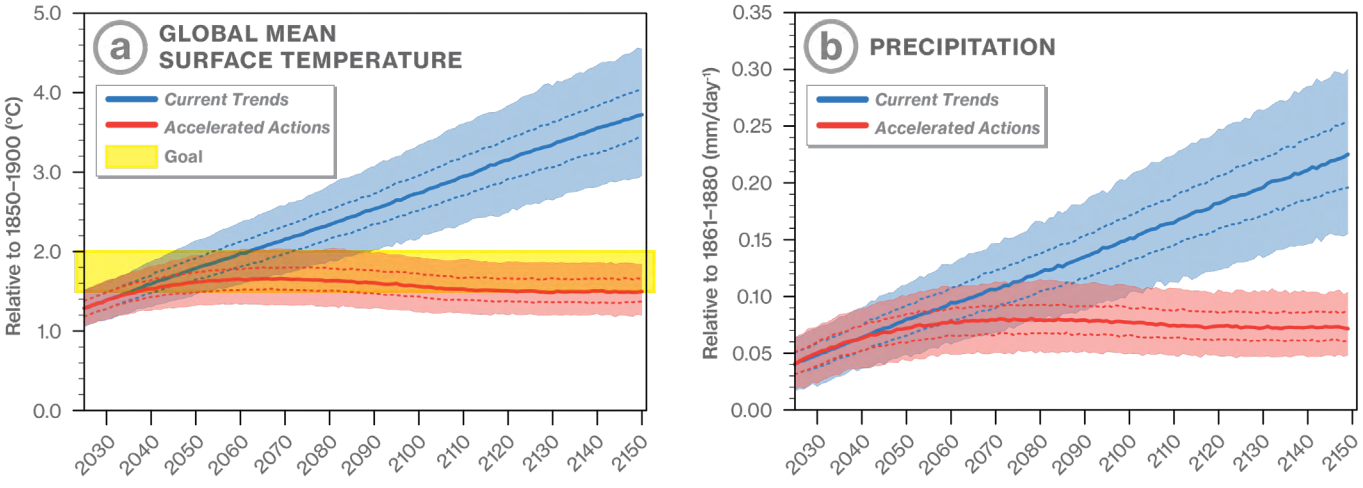


Fig. 15. Annual changes in global mean surface-air temperature (a) and precipitation rate (b) under *Current Trends* and *Accelerated Actions*. Changes are calculated from the 1861-1880 ("pre-industrial") mean. In each panel, the solid line represents the median result of the IGSM ensemble, the dashed lines the interquartile range, and the shaded region the 5th to 95th percentile range of values.

Projections • Temperature and Precipitation



Intensification of the global hydrologic cycle is indicated by increased precipitation and evaporation.

likelihood (i.e. less than 5%) that the warming will exceed 2˚C at 2100.

Meanwhile, a warmer climate will accelerate the global hydrologic cycle—and this is reflected by a balanced increase between global precipitation and evaporation. Under *Current Trends*, we project a steady increase in global precipitation from 2025 levels causing at least an additional 0.05 mm/day rise by 2075 with high probability (i.e., 95% chance). By the end of the century, we project a 75% likelihood that precipitation will increase by 0.1 mm/day. Under *Accelerated Actions*, global precipitation increases peak through the 2070's, with a low likelihood (less than 5% chance) that any increase will exceed 0.05 mm/day. In practical terms, 0.05 mm/day accumulates to 9,300 km^3 (about 2.5 quadrillion gallons, or 9.45 quadrillion liters) of water that will circulate through the global hydrologic cycle each year, which slightly exceeds the global human footprint on water resources, estimated at 9,100 km^3 per year.

Implications

Substantially lower increases in global mean surface temperature are highly likely with aggressive emissions cuts: the *Accelerated Actions* scenario offers a greater than 95% chance of staying below 2°C warming. Increased global precipitation (balanced by increased global evaporation) indicates an acceleration of the global hydrologic cycle. Yet other research findings in this report indicate that this global acceleration reflects important regional patterns of more intense storms, flood risks and water resource shortages.

Author: C. Adam Schlosser

Extreme Precipitation Events

Context

Extreme precipitation is expected to become more frequent and intense as a result of increased atmospheric moisture associated with global warming. However, precipitation projections in current climate models, which typically have coarse spatial resolutions (>100 km), are not very reliable for characterizing localized extremes[1,2], due to the models' inability to represent small-scale features (e.g., clouds and terrain) critical for precipitation processes. Nevertheless, large-scale meteorological patterns (LSMPs) accompanying extreme precipitation are well resolved by these models and may extract untapped predictability of localized extreme precipitation occurrences[3].

Actions aiming to reduce global warming could significantly reduce extreme precipitation events.



Recent advances in artificial intelligence have shown the potential capability of deep learning techniques to improve understanding and prediction of extreme precipitation[4,5]. We developed and implemented a deep learning-based convolutional neural network model to predict winter season (December-January-February) extreme precipitation occurrence changes across the state of California. These predictions are based on daily LSMPs simulated by our coupled Integrated Global System Modeling and Community Earth System Model framework (IGSM-CESM1) under the *Current Trends* scenario. Within this structure, we examine three climate sensitivity cases, each representing a different level of global warming: low (2.0°C), medium (3.15°C) and high (5.3°C). Both low and high climate sensitivities are adjusted for aerosol forcing.

While other LSMPs may be used, our proof of concept is demonstrated based on daily moisture flux anomalies—deviations from the long-term season mean values of integrated water vapor transport for each day. We train our neural network model to predict extreme precipitation occurrences (with a binary classification

1 DeAngelis, A.M., *et al.* (2013). A comparison of CMIP3 simulations of precipitation over North America with observations: Daily statistics and circulation features accompanying extreme events. *J. Climate*, 26, 3209–3230, doi:10.1175/JCLI-D-12-00374.1.

2 Gao, X., *et al.* (2014). An analogue approach to identify heavy precipitation events: Evaluation and application to CMIP5 climate models in the United States. *J. Climate*, 27, 5941–5963. doi:10.1175/JCLI-D-13-00598.1.

3 Gao, X., *et al.* (2017). Twenty-First-Century Changes in U.S. Regional Heavy Precipitation Frequency Based on Resolved Atmospheric Patterns. *J. Climate*, 30, 2501–2521. doi:10.1175/JCLI-D-16-0544.1.

4 Davenport, F.V., & Diffenbaugh, N.S. (2021). Using machine learning to analyze physical causes of climate change: A case study of U.S. Midwest extreme precipitation. *Geophys Res Lett*, *48*, e2021GL093787. doi:10.1029/2021GL093787

5 Gao, X., & S. Mathur (2021). Predictability of U.S. Regional Extreme Precipitation Occurrence Based on Large-Scale Meteorological Patterns (LSMPs). *J. Climate*, 34, 7181–7198. doi:10.1175/JCLI-D-21-0137.1.

Projections • Extreme Precipitation Events

of extreme versus non-extreme day) using the European Centre for Medium-Range Weather Forecasts Reanalysis V5 (ERA5) daily moisture flux anomalies from Dec-Feb of 1980-2005—a set of 25 consecutive winter seasons (see **Fig. 16**). The trained neural network model then analyzes moisture flux anomalies from the IGSM-CESM1 historical (1954–2005) and future (2006–2101) simulations. Finally, for each climate sensitivity, we quantify the change in extreme precipitation occurrences by comparing seven 25-year winter-season sets—each set centered on a specific year (see **Fig. 17**)—to the 1980–2005 historical value.

Key Findings

Extreme precipitation occurrences at both medium and high climate sensitivities show pronounced increases, with 0.7–3.6 (medium) and 0.6–3.0 (high) more events per year throughout the examined periods. This upward trend is generally consistent with the progression of time, with larger increases occurring in later periods.

The potential benefit of reduced warming on reducing extreme precipitation occurrences is evident, as low climate sensitivity shows decreases (0.8–1.6 fewer events per year) throughout the first four periods and less pronounced increases (0.6–1.1 more events per year) during late periods. In all three cases, more extreme precipitation events are predicted for the California winter seasons from 2050 forward.

Implications

Climate actions aimed at reducing global warming can lead to a notable reduction of extreme precipitation events. In particular, reliable prediction in future changes to extreme precipitation occurrence could provide important guidance for the public and policymakers to prepare for the consequences of climate change. The developed convolutional neural network model can be easily implemented with other LSMPs and readily applied to other regions of interest across the globe.

Author: Xiang Gao

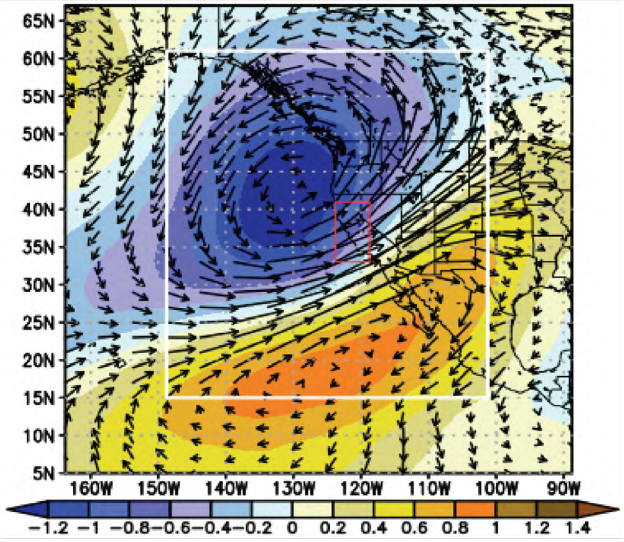


Fig. 16. Composite standardized anomalies of the ERA5 zonal and meridional vertically integrated daily moisture fluxes (arrows) and geopotential height (shaded) for California (red rectangle) based on observed winter extreme precipitation events (exceeding 99.5th percentile) from Dec. 1980-Feb. 2020. White rectangle shows a spatial domain to extract the relevant LSMPs.

Our extreme-precipitation prediction model can be easily trained with large-scale meteorological patterns and applied to other regions of interest across the globe.

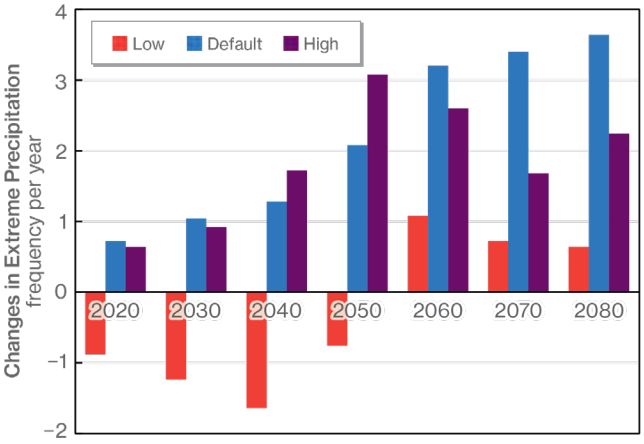


Fig. 17. Projected changes in California winter season extreme precipitation occurences at three climate sensitivities under the *Current Trends* scenario. Model predictions based on the daily total moisture flux.

Extratropical Cyclones

Context

While many studies have investigated the impact of climate change on tropical cyclones (hurricanes), generally projecting an increase in intensity[1], less work has focused on climate impacts on extra tropical cyclones (ETC). ETCs, which form outside the tropics, are a defining feature of weather at mid- and high latitudes. They shape rainfall, winds and temperature variability across North America, Europe and southern Africa, and strongly influence shipping, agriculture and energy systems. Anticipating how ETCs evolve in a warming climate is therefore critical for assessing future risks. A key uncertainty in climate science is climate sensitivity (CS), or the amount of global warming that occurs if atmospheric carbon dioxide doubles. Estimates range from 2.0°C to 5.3°C, but the exact value remains uncertain due to feedbacks, particularly those involving clouds. Our Earth-system modeling framework tests across this range while reproducing recent observed warming. We identify and track storms using the method described in a recent paper[2], which follows individual systems across the mid-latitudes (30°–60°N for the Northern Hemisphere (NH) and 30°–60°S for the Southern Hemisphere (SH)). Two periods are compared under the *Current Trends* scenario using low (2.0°C), medium (3.15°C) and high (5.3°C) CS experiments: a historical baseline (1986–2005) and a mid-century future (2041–2060).

In some regions, projected increases in storm activity amplify risks in the occurrence of storm-driven rainfall and wind extremes.

Key Findings

The total number of extratropical cyclones across the mid-latitudes is projected to decrease modestly by mid-century relative to the historical baseline. The reduction is more consistent across CS experiments in the NH, while SH changes vary among experiments. In the historical period, SH storms are systematically stronger than those in the NH, and this contrast persists in mid-century projections. Median intensities show no systematic increase or decrease, indicating that storm strength remains relatively constant through mid-century (**Fig. 18**).

1 https://www.climate.gov/news-features/understanding-climate/climate-change-probably-increasing-intensity-tropical-cyclones

2 Chinta, S., *et al.* (2025). Future changes in winter-time extratropical cyclones over South Africa from CORDEX-CORE simulations. *Earth's Future*, *13*(I), e2024EF005289 (doi:10.1029/2024EF005289).

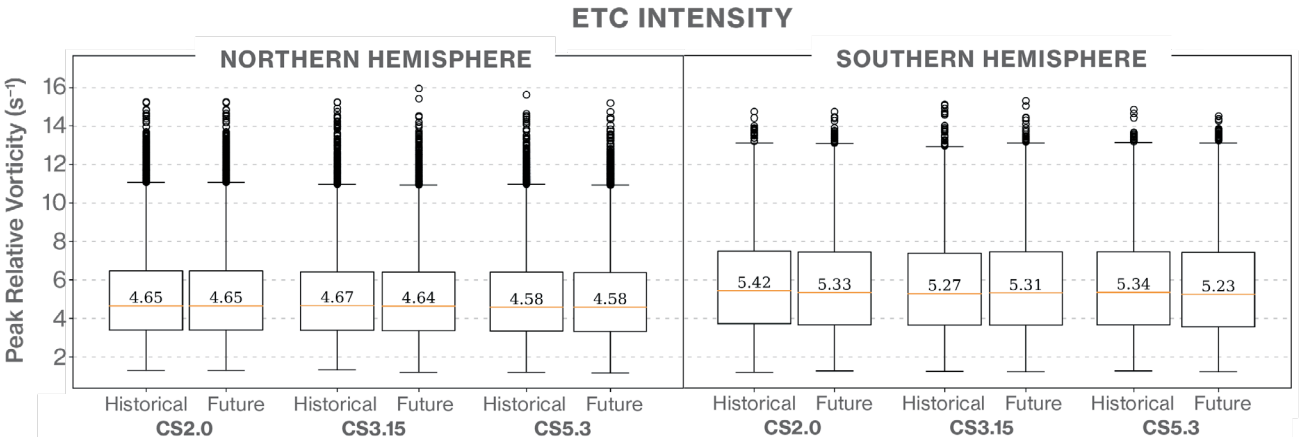


Fig. 18. ETC intensity comparison for NH/SH hemispheres and different climate sensitivities. Intensity is defined as "peak relative vorticity," which essentially quantifies the maximum "spin" of every ETC center that is tracked. The box and whisker plots denote median (solid red line), interquartile range (boxed area), and 5th-95th percentiles (whiskers) of all individual storms tracked within the analysis periods.

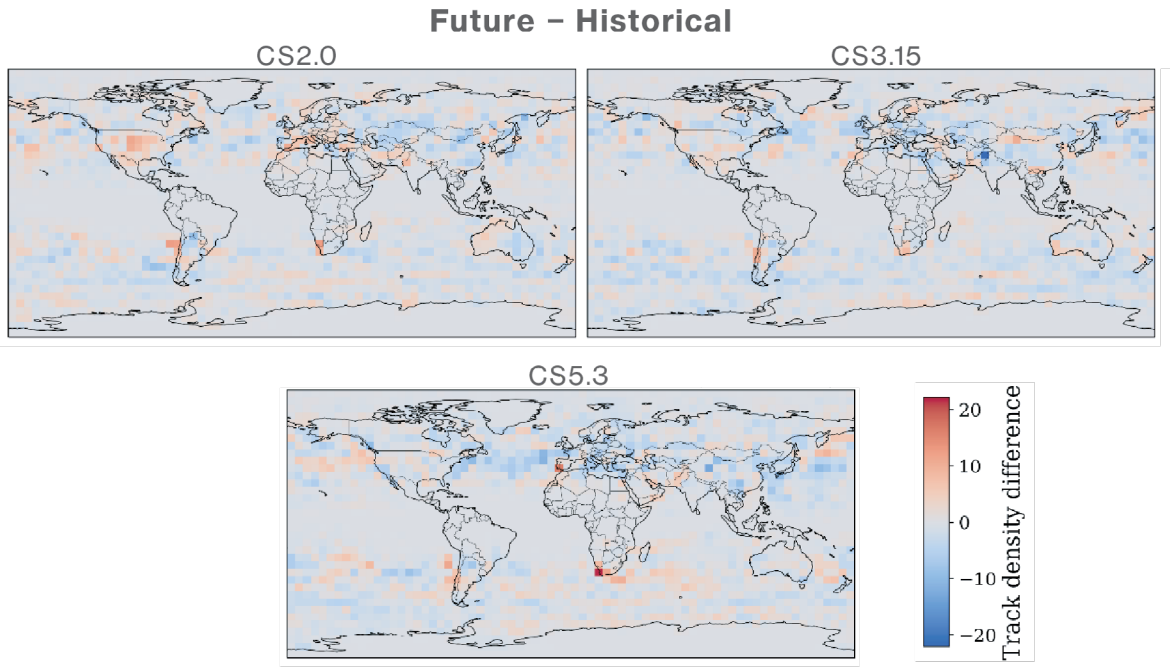


Fig. 19. Projected changes in global ETC track density for three climate sensitivity experiments (CS2.0, CS3.15, CS5.3), shown as future (2041–2060) minus historical (1986–2005).

The regions where ETCs most often travel, including the North Atlantic, the North Pacific, and the storm belt circling the Southern Ocean, remain largely unchanged. By mid-century, storm activity increases, particularly south of Africa and in parts of the Southern Ocean. In the Northern Hemisphere, changes are smaller and vary both by continental regions and by CS experiment (**Fig. 19**). By mid-century, the latitude of peak storm activity remains nearly unchanged, and poleward migration is minimal. Across all three experiments, the aggregate statistics of mid-latitude ETCs (**Fig. 18**) are strikingly consistent. However, the spatial distribution of projected changes (**Fig. 19**) varies notably across CS configurations, indicating that regional storm responses are more sensitive to uncertainty in climate sensitivity.

Implications

On average, ETCs identified in our analysis are projected to decline slightly in number and remain constant in intensity through mid-century. This suggests that ETC-related risks may not increase sharply by 2060.

Regional patterns, however, reveal important signals. Projected increases in storm activity south of Africa and across parts of the Southern Ocean could amplify risks of storm-driven rainfall and wind extremes in these regions. In contrast, NH changes remain smaller and less consistent, making them harder to interpret with confidence.

Looking ahead, the muted response in the near term does not preclude larger changes later in the century. Stronger warming could still drive more substantial shifts in storm behavior, with broader implications for climate and society.

Authors: Sandeep Chinta and C. Adam Schlosser

We acknowledge the contributions of Kevin Hodges, University of Reading, for helping with the implementation of the cyclone tracking algorithm.

Box 8. Emulation: Challenge and Promise

Emulators promise to accelerate future climate and sustainability assessments.

What is a climate emulator?

Climate emulators are lightweight, data-driven models that reproduce the outputs of full-scale climate models without explicitly simulating the physics of the climate system[1]. Unlike simple climate models, which have existed for decades and generally output globally averaged values, climate emulators leverage advanced computational techniques, including machine learning, to make climate projections at regional and grid-cell scales.

Why are they useful?

The main advantage of emulators is their speed[1,2]. They can produce climate projections at the same resolution as the original model in a fraction of the time, allowing researchers to explore the space of possible scenarios more efficiently. While climate emulators to project single variables such as temperature were first developed in the 1990s[3], today's techniques can now replicate multiple spatially and temporally correlated climate variables, while capturing the full distribution of possible outcomes[4,5,6].

Applications in this Outlook

"Air Quality and Health" on page 32 shows projections of anthropogenic $PM_{2.5}$ for the *Current Legislation* (CLE) and *Maximum Feasible Reduction* (MFR, more air pollution control) scenarios produced by a novel air quality emulator developed by our team[7]. The emulator estimates grid-cell level changes in $PM_{2.5}$ and associated global changes in premature mortality at a 95% confidence interval. Crucially, this emulator runs a full scenario in less than ten seconds of CPU time, a task that requires roughly 3,000 CPU hours for the original, full-scale model.

Challenges and the promise of emulation

Emulation promises to fundamentally shift climate impact assessment. While the science behind emulators is rapidly maturing, the next major step is integrating them into assessment frameworks such as the MIT Integrated Global System Modeling (IGSM) framework. Building on CS3's history of conducting targeted assessment of changes including uncertainty, the speed and spatial resolution of emulators will allow us to provide quicker, more targeted analyses on topics of relevance to decision-makers. We are actively developing emulators for key impact variables, including monthly temperature (max, min and average), precipitation, relative humidity, and wind fields. Emulators can overcome the computational bottlenecks that currently limit our ability to couple climate and economic models in real-time. Using emulators, we will soon be able to provide more frequent updates to our scenarios to enable actionable climate and sustainability analyses under rapidly-changing policy and economic conditions.

Authors: Chris Womack and Noelle Selin

1 Tebaldi, C., *et al.* (2025). Emulators of climate model output. *Annual Review of Environment and Resources*, 50 (doi:10.1146/annurev-environ-012125-085838).

2 Sudakow, I., *et al.* (2022). Statistical mechanics in climate emulation: Challenges and perspectives. *Environmental Data Science*, 1, e16 (doi:10.1017/eds.2022.15).

3 Santer, B.D., *et al.* (1990). Developing climate scenarios from equilibrium GCM results. Max Planck Institute for Meteorology, Report #47.

4 Watson-Parris, D., *et al.* (2022). ClimateBench v1.0: A benchmark for data-driven climate projections. *Journal of Advances in Modeling Earth Systems*, 14(10), e2021MS002954 (doi:10.1029/2021MS002954).

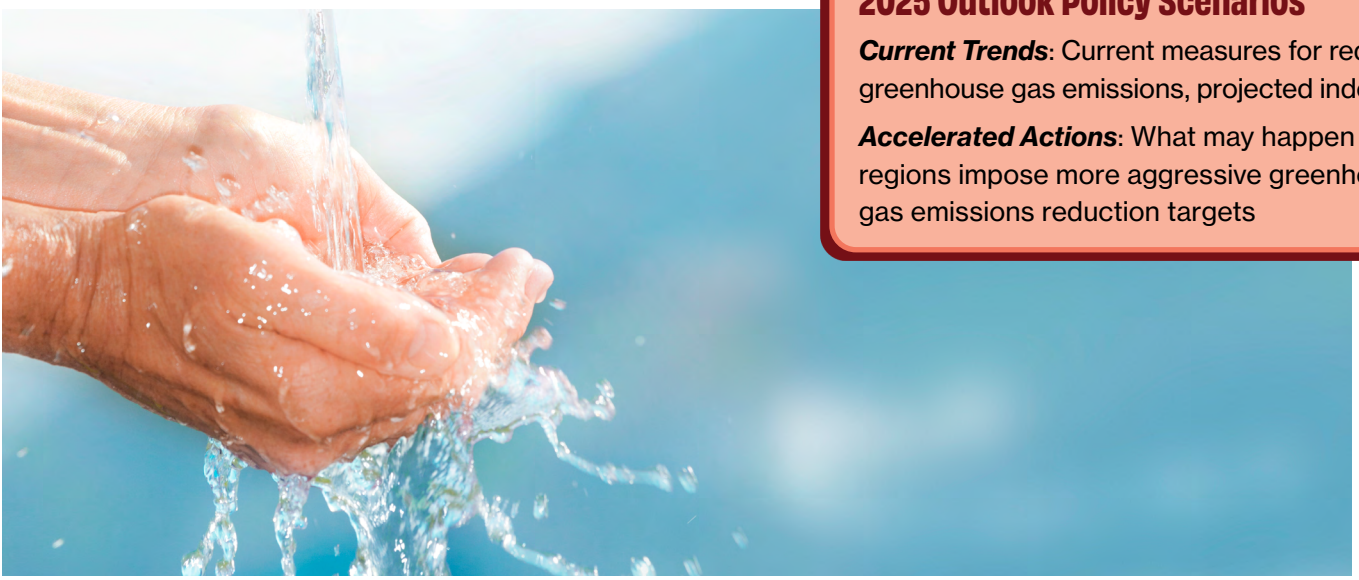
5 Bassetti, S., *et al.* (2024). Diffesm: Conditional emulation of temperature and precipitation in earth system models with 3d diffusion models. *Journal of Advances in Modeling Earth Systems*, 16(10), e2023MS004194 (doi: 10.1029/2023MS004194).

6 Bouabid, S., Sejdinovic, D., & Watson-Parris, D. (2024). FaIRGP: A Bayesian energy balance model for surface temperatures emulation. *Journal of Advances in Modeling Earth Systems*, 16(6), e2023MS003926 (doi:10.1029/2023MS003926).

7 Wong, A.Y., *et al.* (2025). A Geographically Weighted Gaussian Process Regression Emulator of the GCHP 13.0. 0 Global Air Quality Model. *EGUsphere*, 2025, 1-33 (doi:10.5194/egusphere-2025-2663).

Implications for Sustainability

Short- and Long-term Risks to Human Well-Being



2025 Outlook Policy Scenarios

Current Trends: Current measures for reducing greenhouse gas emissions, projected indefinitely

Accelerated Actions: What may happen if regions impose more aggressive greenhouse gas emissions reduction targets

Water

*Climate policies aligned with **Accelerated Actions** can yield substantial co-benefits for water availability.*

Context

Key considerations in sustaining water resources include potential impacts on its availability and quality and the effectiveness of different actions to mitigate increasing risks. Our prior research findings have shown that at a global scale, low-carbon, climate mitigation policies and targets provide marginal benefits to water scarcity trends. However, these global assessments may mask important regional basin details on co-evolving system-wide pressures. In addition, water-quality risk assessments require a more granular approach—necessitating the use of more detailed water-system modeling of supply, demand, nutrient loading, and conveyance.

To that end, our water impact modeling framework consists of a suite of linked models that represent various aspects of the natural and managed water system. The model represents riverine and groundwater resources, which are allocated across water demand sectors. The resulting managed flow is then delivered to a computationally efficient water quality model that provides a suite of metrics to quantify impacts relevant to aquatic systems and human health.

This modeling framework, driven by our *Current Trends* and *Accelerated Actions* scenarios, assesses potential responses due to changes in climate and weather, as well as human activities and demands. Our downscaling methods also allow us to consider the total range of plausible regional patterns of change in climate (i.e., wetter or drier outcomes)—adding quantitative insights to the potential range of risks. Our framework enables highly resolved projections across large continental basins of interest. Among these, the Mississippi River Basin (MRB) is among the most compelling in the world in terms of size, physical and economic flows, as well as the range of hydroclimates it spans.

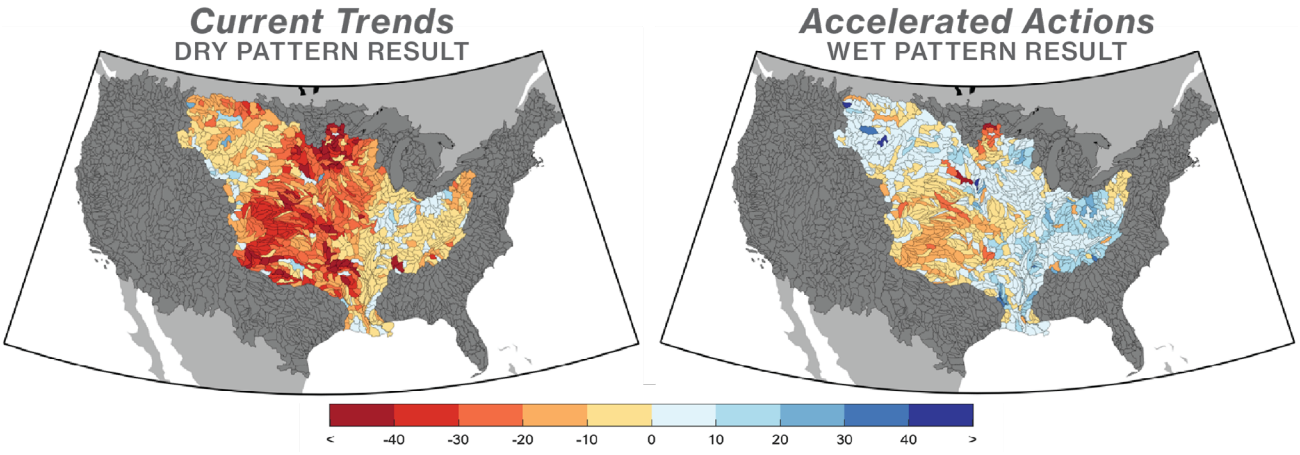


Fig. 20. Percent changes in managed mean annual river flow as simulated by the water impact framework. Maps show difference between mid-century average (2041-2060) and baseline historical period (2001-2020).

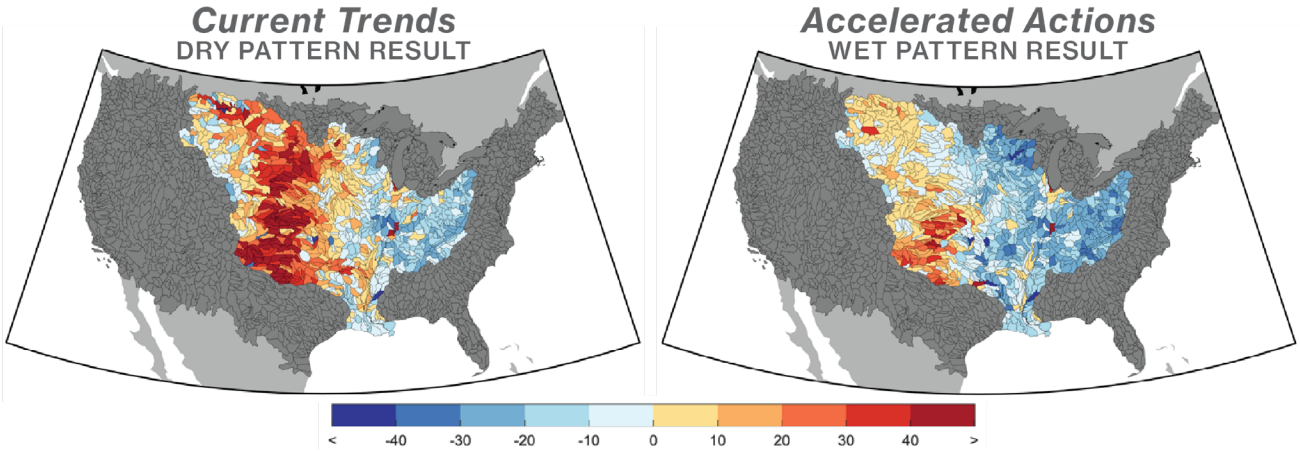


Fig. 21. Percent changes in water stress index (total withdrawals vs. total available water) as simulated by the water management module within the water-impact framework. Maps show difference between mid-century average (2041-2060) and baseline historical period (2001-2020).

Key Findings

Changes in managed river flow over the MRB demonstrate a wide range of trends to plausible climate shifts under *Current Trends* and *Accelerated Actions* (**Fig. 20**). While a "dry" climate trend pattern in *Current Trends* produces widespread decreases, a "wet" trend pattern in *Accelerated Actions* can result in increases across a majority of the (845) represented basins. Nevertheless, decreases in managed river flow can still result in *Accelerated Actions* due to outpacing water demands. Overall, these competing factors can be seen in projected water stress trends (**Fig. 21**) with widespread increases from the "dry" evolving pattern under *Current Trends*. The benefit of more aggressive climate action could be substantial, with the resultant number of increasing water stress trends cut almost in half for the *Accelerated Actions* "wet" result. On the other hand, water quality in these projections (**Fig. 22**) follows a more complex set of factors, and the benefit of climate action is not as widespread. In this example, while reductions in the water quality index (a diagnostic that combines levels of nitrogen, phosphorus, dissolved oxygen, cyanobacteria and temperature) occur in fewer basins for the *Accelerated Actions* case, nearly half of the MRB basins could still experience lower water quality.

Implications

Climate actions can yield substantial co-benefits for water availability, particularly at local and

Implications for Sustainability • Water

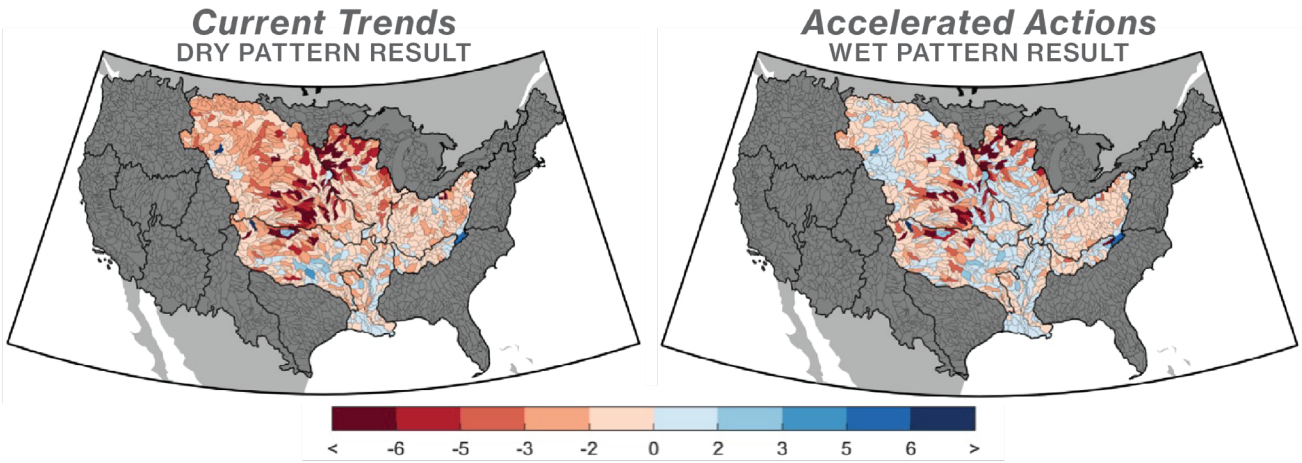
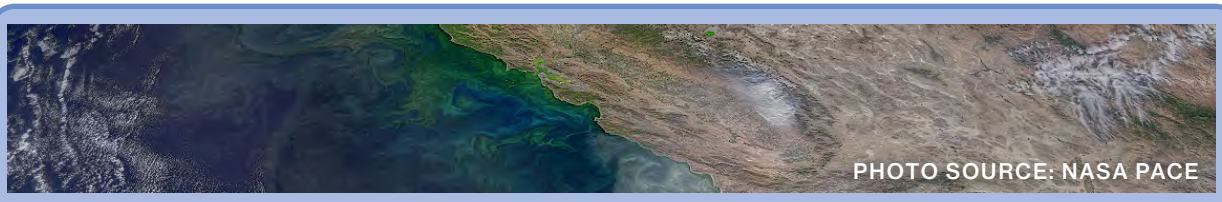


Fig. 22. Changes in water quality index as simulated by the water management module within the water-impact framework. Maps show difference between mid-century average (2041-2060) and baseline historical period (2001-2020). Negative values indicate a decrease in overall water quality.

regional scales. However, to identify strategies for sustainable water resources, additional complex factors that influence water quality must be incorporated. Developing such comprehensive and integrated solutions depends on the expanded availability of detailed data, advanced modeling frameworks, and robust analytical approaches.

Author: C. Adam Schlosser



Box 9. Changes in ocean color indicate potential risks for marine ecosystems

Covering more than 70% of the Earth's surface, the oceans play a crucial role in regulating climate, transporting and storing heat and carbon. Scientists estimate that the oceans have absorbed about 30% of anthropogenically emitted carbon and over 90% of the excess heat trapped by anthropogenic greenhouse gases. Though absorbing carbon and heat from the atmosphere has helped limit the increase in air temperature, it has likely led to significant changes in the ocean's circulation and ecosystems. However, documenting these trends is difficult due to large natural interannual variability in the ocean. Traditionally, scientists have focused on monitoring physical changes to the ocean (e.g., changes in temperature and currents) and comparing those changes to numerical simulations of the future climate. Exploring the biology of the ocean offers an alternative route.

Phytoplankton are microscopic, single-celled organisms that form the base of the marine food web and are crucial in the ocean's ability to store carbon. These "plant-like" organisms photosynthesize, capturing the sun's energy, and use carbon dioxide to produce carbohydrates. Different concentrations and combinations of these highly diverse phytoplankton alter the color of the ocean and can be monitored by satellite sensors. With statistical probing of the NASA MODIS satellite record, a recent study found that about half of the ocean has experienced a change in ocean color over the last 20 years, with some places becoming bluer and others greener. The study used CS3 climate simulations along with the MIT marine ecosystem model (Darwin) to show that the observed trends are consistent with anthropogenically driven climate change. Such changes in ocean color signal an ongoing alteration of the base of the marine food web, with risks for fish, marine mammals and humans.

More information: MIT News article

Authors: Stephanie Dutkiewicz and Jeffery Scott

Biodiversity



Biodiversity protection policies can be synergistic with emissions reduction policies.

Context

Limiting global warming to 1.5°C will require significant land-use change. Several strategies designed to meet the long-term targets of the Paris Agreement are rooted in land-based carbon dioxide removal methods. However, these strategies may not align with biodiversity conservation policies. We assess the compatibility of the U.N. Kunming-Montreal Global Biodiversity Framework's 30x30 Biodiversity Goal—protecting 30% of land and oceans with high biodiversity and ecosystem functions by 2030—with the *Current Trends* and *Accelerated Actions* scenarios. In particular, we assess the added cost of achieving the 30x30 goal under each scenario. To do this, we augment the *Current Trends* and *Accelerated Actions* scenarios by protecting high biodiversity natural forest and grasslands through incentivizing subsidy-based transition to these land types.

Key Findings

Results show that under *Current Trends,* the EPPA regions of India, the Middle East, Africa and Other East Asia experience the largest declines in GDP under a 30x30 scenario versus a baseline scenario without a 30x30 goal. Meanwhile, Brazil, Latin America, United States, Australia and New Zealand experience experience slight GDP growth with the 30x30 goal (**Fig. 23**). Overall, these results highlight challenges for regions with deficient natural forest and grassland cover, but also a potential comparative advantage for strong agriculture and livestock regions that would benefit from increased food exports.

Our results also show that a weaker climate change policy would lead to higher costs to reach the 30x30 goal, with smaller declines in GDP across economic regions in *Accelerated Actions* relative to *Current Trends* (**Fig. 24**). Higher taxation on carbon and investment for decarbonization could reduce consumption and consequently disincentivize land conversion of natural capital. As a result, with a more stringent *Accelerated Actions* climate target, a concurrent 30x30 policy could require fewer subsidies to reach biodiversity targets, especially in the Middle East, India, Africa and Other East Asia.

We find that in most EPPA regions (see **Fig. 25**), a 30x30 policy (blue) produces significantly smaller perturbations to GDP compared to stringent climate policy scenarios such as *Accelerated Actions* (red). The one exception is the Middle East, where the cost of achieving the 30x30 could be comparable to the cost of meeting an *Accelerated Actions* scenario. Importantly, pursuing both policies together (green) creates synergies that generally result in lower GDP impacts than the sum of the individual policies (purple). Further, in most regions, the cost of the combined policy (green) is only marginally higher than the cost of *Accelerated Actions* alone (red).

Implications

A decrease in available land for agriculture and livestock could increase reliance on imports to compensate for food demand. Therefore, a 30x30 policy may place further pressure on regions that serve as major exporters of crops and livestock. If 30x30 is to achieve a net gain in biodiversity, it is imperative to complement it with policies that regulate domestic deforestation, track food import-related land-use, and incentivize sustainable agricultural intensification.

Modeled results further show that a 30x30 biodiversity target has a significantly lower GDP impact at the regional level than reaching a stringent *Accelerated Actions* climate policy. Hence, it signals the feasibility of deploying both biodiversity and climate goals simultaneously, as well as adding incentives for economic regions to protect valuable biodiversity and ecosystem services without significantly impacting their GDP.

Authors: Kevin Lin Yang, C. Adam Schlosser and Angelo Gurgel

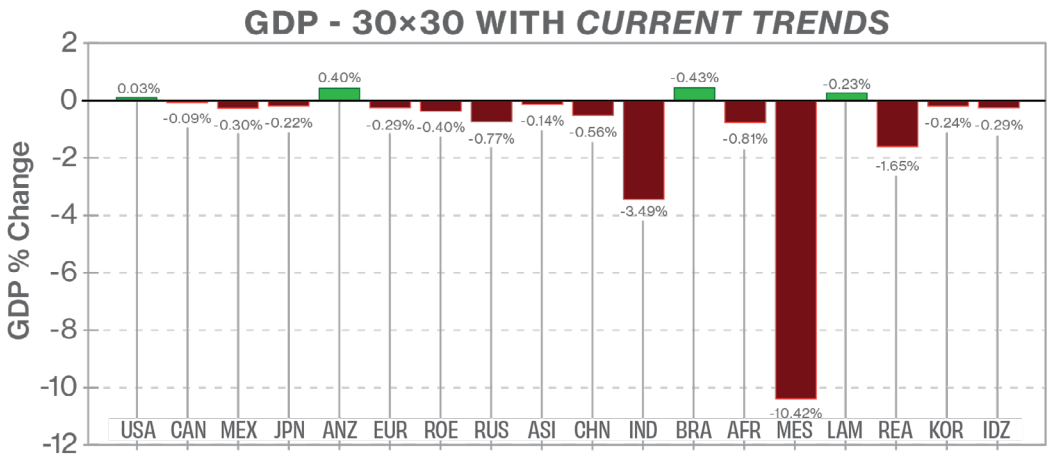


Fig. 23. GDP percentage change for each EPPA region by 2030. GDP with *Current Trends* and implemented 30x30 target subsidies subtracted from a base *Current Trends* scenario without the subsidies.

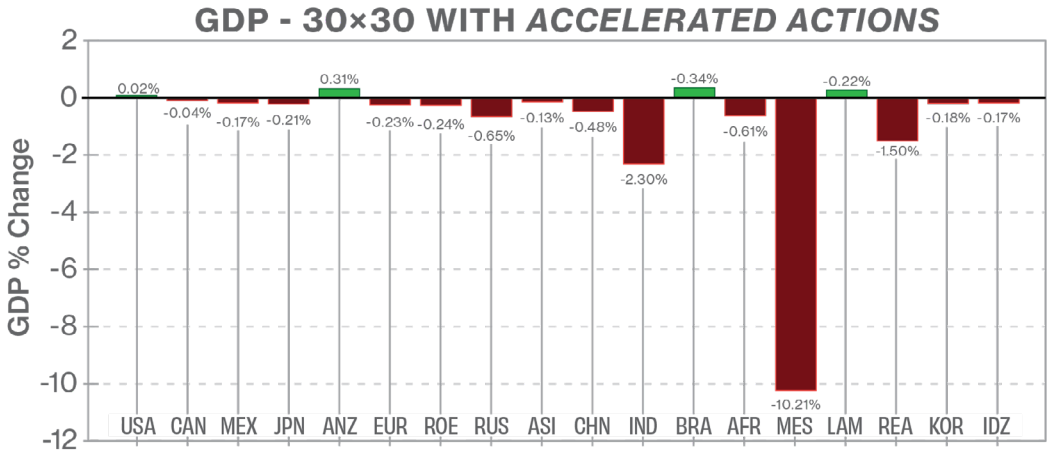


Fig. 24. GDP percentage change for each EPPA region by 2030. GDP with *Accelerated Actions* and implemented 30x30 target subsidies subtracted from a base *Accelerated Actions* scenario without the subsidies.

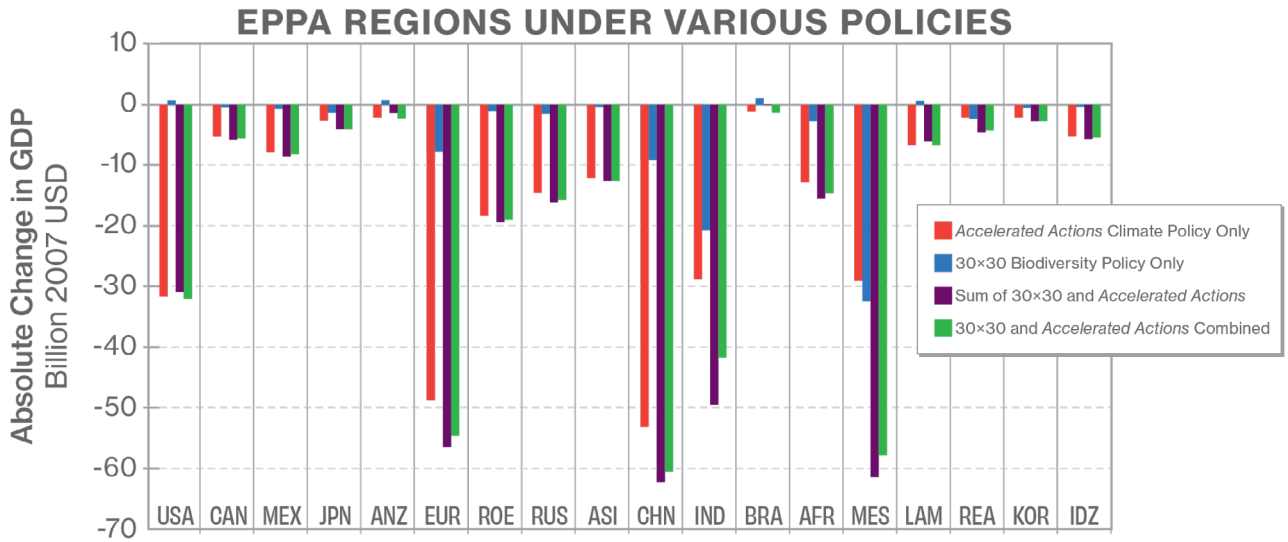


Fig. 25. Bar plot representation of the absolute change in GDP (Billion 2007 USD) by EPPA region benchmarked against a base *Current Trends* without a 30x30 baseline scenario.

Air Quality and Health

Combining climate and air quality policies can minimize air pollution and associated health impacts.

Context

Greenhouse gases and air pollutants are often co-emitted, especially when combustion is involved (e.g., via power plant smokestacks or automobile exhaust pipes). Some climate solutions, such as the deployment of renewable energy systems[1] and electric vehicles[2], deliver substantial economic and societal benefits by improving air quality and associated health outcomes. Climate change can also directly impact air pollution levels by altering meteorological conditions[3]. Therefore, including air quality effects is essential to holistically understanding the overall impacts of climate policies.

Here we study the trajectory of global air pollution under both *Current Trends* and *Accelerated Actions* scenarios. We further subdivide *Current Trends* and *Accelerated Actions* by two assumed bounding cases of air-pollution control levels that are set independently from climate policy: 1) Current Legislation (CLE, the lower bound) and 2) Maximum Feasible Reduction (MFR, the upper bound)[4], resulting in four scenarios (CT_CLE, CT_MFR, AA_CLE, AA_MFR).

Key findings

We use the Tool for Air Pollution Scenarios[5] to project air pollutant emissions at each MIT Economic Projection and Policy Analysis (EPPA)

1 e.g. Dimanchev, E. *et al.* (2019). Health co-benefits of sub-national renewable energy policy in the US. *Environ. Res. Lett.*, 14, 085012 (doi:10.1088/1748-9326/ab3id9).

2 e.g. Choma, E.F., *et al.* (2020). Assessing the health impacts of electric vehicles through air pollution in the United States. *Environment International*, 144, 106015 (doi:10.1016/j.envint.2020.106015).

3 Jacob, D.J. and Winner, D.A. (2009). Effect of climate change on air quality. *Atmospheric Environment*, 43, 51–63 (doi:10.1016/j.atmosenv.2008.09.051).

4 GAINS Developer Team (2021). GAINS 4.01 IAM model outputs, IIASA.

5 Atkinson, W., *et al.* (2022). A tool for air pollution scenarios (TAPS v1.0) to enable global, long-term, and flexible study of climate and air quality policies. *Geosci. Model Dev.*, 15, 7767–7789 (doi:10.5194/gmd-15-7767-2022).

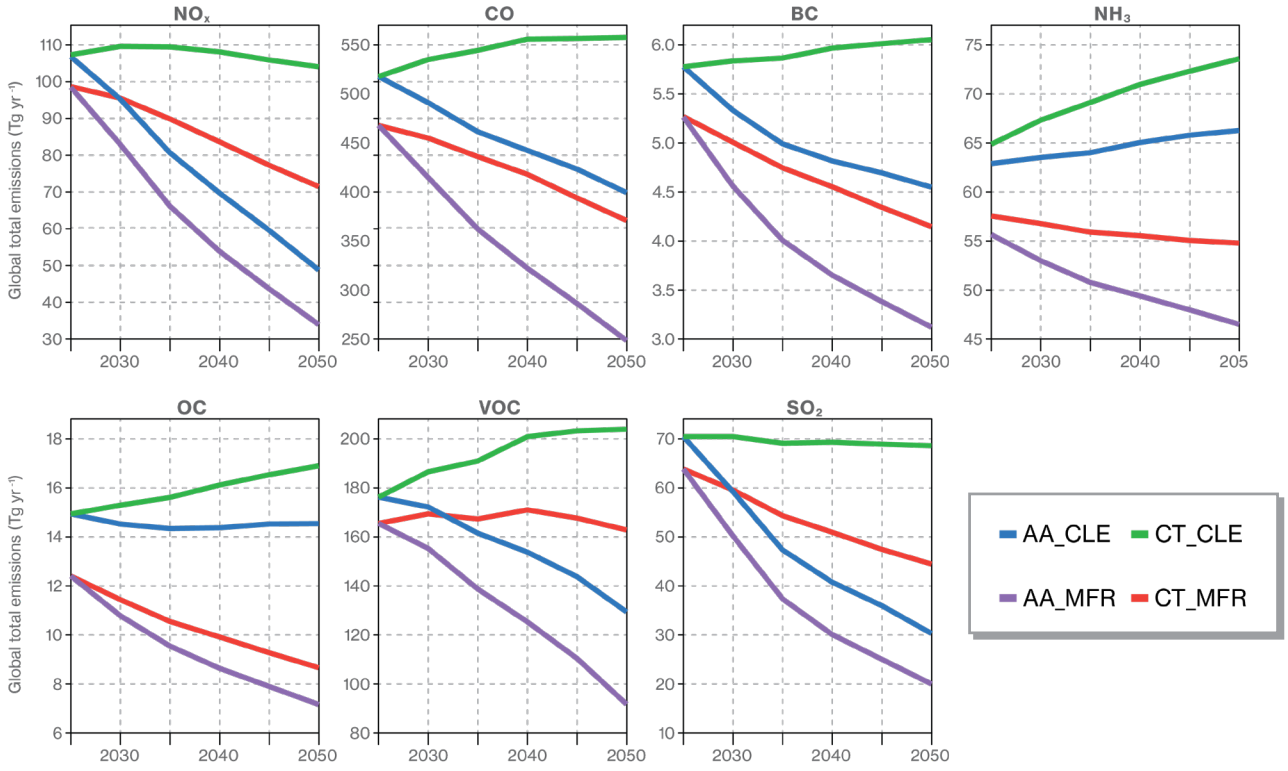


Fig. 26. Projected trends in air pollutant emissions from 2025 to 2050 under the four scenarios studied

Implications for Sustainability • Air Quality and Health

model region, which fuses energy consumption (provided by EPPA) and assumed air pollution control level, and the result is shown in **Fig. 26**. We find that under *Current Trends* (CT_CLE, green), air-pollutant emissions increase globally except for SO_2 and NO_x, which are projected to decrease slightly by 2050 (-2.9% for NO_x and -2.6% for SO_2, relative to 2025 levels). Climate policy (blue), which limits fossil fuel combustion, is generally more effective (e.g., -57% for SO_2 and -54% for NO_x by 2050) in controlling combustion-sourced air pollutants than direct air pollution control policies (red) (e.g., -27% for SO_2 and -27% for NO_x by 2050). In contrast, climate policy (blue) (+5.4% by 2050) is less effective in controlling ammonia emissions (mostly from agriculture) than stringent direct air pollution control policy (red) (-4.8% by 2050). Combining climate and strong air quality policy (purple) provides significantly bigger reductions in emissions for all air pollutants (e.g., -65% for SO_2, -65% NO_x and -16% for NH_3 by 2050).

We next feed air pollutant emissions and greenhouse gas concentrations from each scenario into our newly developed global air quality emulator[6], which can provide $PM_{2.5}$ (fine particulate matter, the most important ambient air pollutant globally) projections within seconds. **Fig. 27** shows the resulting trajectories of global premature mortalities attributable to $PM_{2.5}$ pollution over 2025–2050. Under *Current Trends* with current levels of air pollution controls (green), global $PM_{2.5}$ pollution improves only slightly during that period. Stringent air quality policy (red) is more effective than climate policy in improving $PM_{2.5}$ air quality in the near term (up to 2030). After 2030, climate policy (blue) shows higher efficacy in controlling $PM_{2.5}$ pollution. Finally, the combination of climate and strong air quality policies (purple) provides even bigger improvements in $PM_{2.5}$ air quality (saving 1.4–2.0 million people per year globally at 2050).[7]

Implications

Our work shows appreciable health co-benefits from reducing fossil fuel combustion at global scale, and the need for combining climate and air quality policies in minimizing air pollution and the associated health impacts.

Author: Anthony Wong

6 Wong, A.Y.H., *et al.* (2025). A Geographically Weighted Gaussian Process Regression Emulator of the GCHP I3.0.0 Global Air Quality Model. (doi:10.5194/egusphere-2025-2663).

7 Burnett, R., *et al.* (2018): Global estimates of mortality associated with longterm exposure to outdoor fine particulate matter. *PNAS*, 115, 9592–9597 (doi:10.1073/pnas.1803222115).

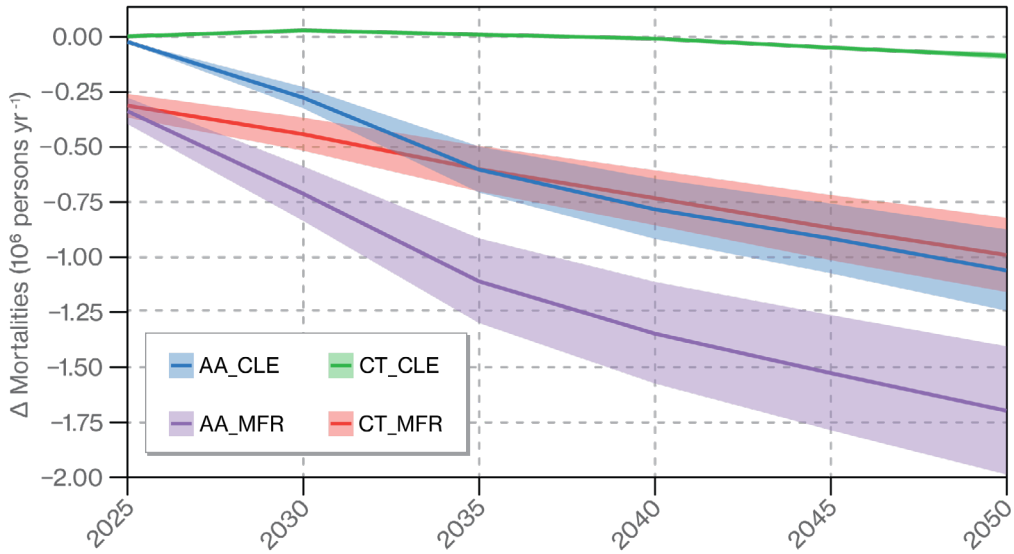


Fig. 27. Projected human-induced changes in annual global premature mortalities attributable to $PM_{2.5}$ from 2025–2050, relative to 2025 business-as-usual (CT_CLE) level. Shades indicate 95% confidence interval due to uncertainty in the epidemiological model relating $PM_{2.5}$ level with premature mortality.[7]

Global Economic Impacts of Climate Change

Context

Climate change impacts vary across sectors and regions, and can propagate through the global economy by affecting supply chains and international trade. Global economy-wide computable general equilibrium (CGE) models are unique in their ability to capture interregional and intersectoral interactions and feedbacks, allowing them to characterize not only the direct economic implications of climate impacts, but also indirect effects and adaptive responses. We demonstrate this with our multi-region, multi-sector global MIT Economic Projection and Policy Analysis (EPPA) model. Based on an estimate of the relationship between climate change and total factor productivity (TFP, a measure of how efficiently resources like capital, labor and land generate output)[1], we simulate country-level TFP shocks for future temperature projections from SSP585, SSP370 and SSP245 (similar to *Current Trends)*—three scenarios defined by imposing a given Shared Socioeconomic Pathway and Representative Concentration Pathway. Importantly, these shocks are simply used as an example to explore the global dynamics of climate impacts, not to reflect our best guess of the magnitude of global climate impacts.

Key Findings

In the year 2100, we find global GDP impacts of -1.4% for SSP585, -1.1% for SSP370 and -0.4% for SPP245, with the majority of the GDP impacts attributed to lower consumption (**Fig. 28**). Countries in East Asia, the Middle East, Brazil, Mexico, India and Africa face the worst GDP impacts, while Canada, Europe and Russia see GDP gains (see **Fig. 29a**). Globally, the sectors most impacted in terms of output are crop, transportation, food, and energy-intensive industry. Within the U.S., the crop sector is impacted far more than any other. To explore how regions are affected by climate impacts in other regions, the

Climate impacts can transmit across regions via international supply chains and trade.

TFP shocks are applied to one region at a time (see **Fig. 29b**), with the results for that region compared to results when the TFP shocks are applied to all regions simultaneously. We find that climate impacts in other regions can amplify or dampen direct domestic climate impacts, in the range of +/- 2.0% by 2100 for SSP585 and +/- 0.6% for SSP245 (see **Fig. 29c**), reflecting a sizable indirect climate impact via supply chain and trade effects.

Implications

The significant transmission of climate impacts across regions suggests that planners need to think carefully about climate impacts in other regions and the resilience of global supply chains. Depending on a country's position in the global economy (supply chains, trade patterns, relative climate vulnerability, etc.), climate impacts elsewhere can either dampen country-level economic impacts or amplify them. Our results also highlight the value of global structural modeling that can explicitly represent global supply chains and trade responses. This is an important consideration in assessing estimates of the economic impacts of climate change, which diverge depending on whether they use statistical/empirical modeling or structural/process-based modeling[2]. While statistical approaches must extrapolate historical relationships into quite different potential futures, structural modeling approaches are able to represent dynamics and behavioral responses based on economic theory, allowing them to simulate future transitions that are not reflected in historical data—in this case how countries respond to and are impacted by climate impacts in other regions under different climate futures.

Author: Jennifer Morris

1 Casey, G., *et al.* (2023). Projecting the Impact of Rising Temperatures: The Role of Macroeconomic Dynamics. *IMF Econ Rev* 71, 688–718 (doi:10.1057/s41308-023-00203-0).

2 Morris, J., *et al.* (2025). Reconciling widely varying estimates of the global economic impacts from climate change. *Nature Climate Change*, 15(2), 124–127 (doi:10.1038/s41558-024-02232-7).

Implications for Sustainability• Global Economic Impacts of Climate Change

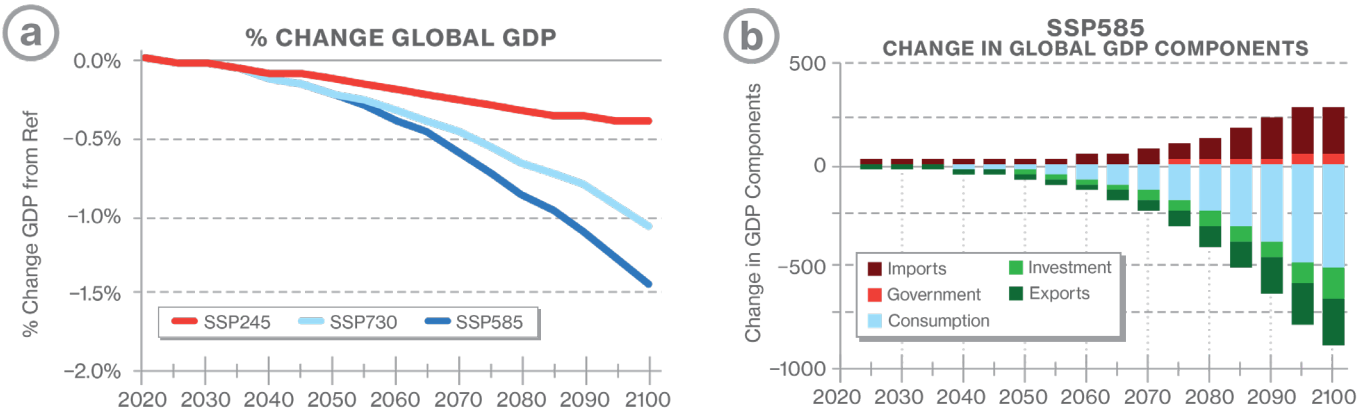


Fig. 28. Percent change in global GDP relative to a reference no-climate-impacts scenario for the SSP585, SSP370 and SSP245 TFP shock scenarios (a); and change in global GDP components for the SSP585 scenario (b).

SSP245 is very similar to the *Current Trends* scenario.

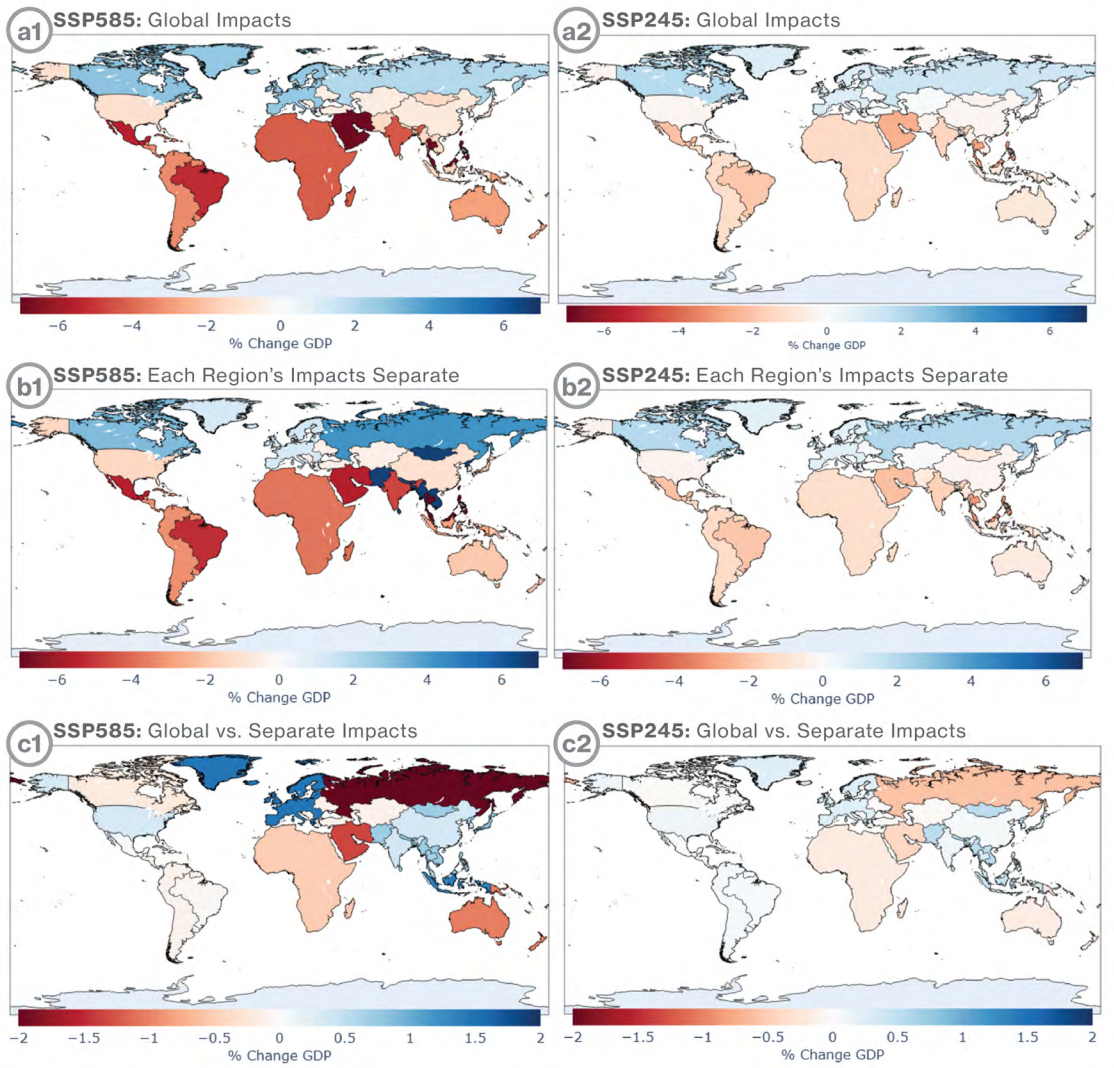


Fig. 29. a1,a2: regional GDP % change relative to reference scenario without climate impacts, TFP shocks applied globally. **b1,b2:** regional GDP % change relative to reference scenario without climate impacts, TFP shocks applied separately to each region (compilation of 18 individual runs). **c1,c2:** regional GDP % change between **a** and **b**. Note color bar scale differences for **c**.

SSP245 is very similar to the *Current Trends* scenario.

US Economic Impacts of Climate Change

Context

Climate change damages sectors directly, and those shocks propagate through the economy. Many assessments evaluate one sector at a time while holding the rest of the economy fixed, so they miss these ripple effects. Rather than take this "partial equilibrium" (PE) approach, we use a general equilibrium (GE), economy-wide model that captures interactions throughout the economy. We link sector damages from the U.S. EPA's Framework for Evaluating Damages and Impacts (FrEDI) to MIT's U.S. Regional Energy Policy model (USREP), a GE model with multiple sectors, regions and income groups. FrEDI provides PE estimates of temperature-driven impacts for buildings, labor, roads and transport through 2100. We translate these into productivity or cost shocks in USREP and simulate GE outcomes. We also assess changes in economic valuation of climate-related deaths. Our simulations use the 2023 Outlook *Current Trends* scenario emissions and temperature trajectories. While the 2025 Outlook updates these inputs, our findings below illustrate the mechanisms at work and amplification—how much economy-wide interactions raise GE outcomes beyond PE-assessed damages.

Climate impacts propagate through the U.S. economy, affecting regions and income groups differently.

Key Findings

- Combined national losses from climate impacts on buildings, labor, roads and transport approach 0.75% of GDP by 2100.
- GE losses exceed PE damages by about 20% by mid-century, about 50% by 2100, and up to 90% for road repair in 2100 (see **Fig. 30**).
- Flood-related transport disruption causes the largest reduction in economic well-being (welfare), reaching 0.54% by 2100 as higher mobility costs suppress consumption (see **Fig. 31**, CONUS yellow bar, for continental U.S. average impact).
- Wind-related building damages, heat-related labor productivity losses, and road repair cut welfare by about 0.09%, 0.04% and 0.04%, respectively, by 2100.
- Impacts are distributed unequally (see **Fig. 31**, circles). Lower-income households bear larger welfare losses when essential service costs rise. In the Flood-Transport scenario, the lowest income group in higher-impact regions faces losses exceeding 6%, far above regional averages.
- Regional disparities are large. Losses in the Southern Plains and Southeast often exceed the national average. Some lower-impact regions gain relative competitiveness as activity and capital shift.
- Amplification of PE impacts happens through intersectoral linkages, interregional trade, reallocation of labor and capital, and household responses.

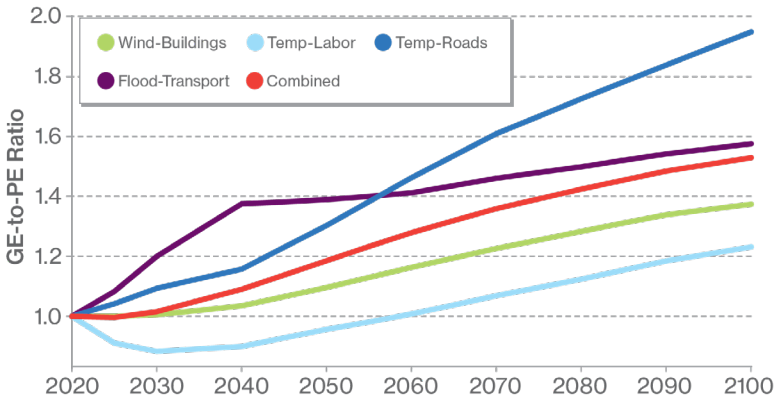


Fig. 30. National GE-to-PE Impact Ratios (2020-2100). GE-to-PE ratios are shown for five climate damage scenarios. Ratios are computed as the GE impacts in terms of GDP loss divided by the PE impacts in each year. For *Wind-Buildings*, the ratio is based on translated damages in terms of lost rental income from building service disruptions, rather than the raw structural damage estimates reported in FrEDI.

Implications for Sustainability • US Economic Impacts of Climate Change

- Reduced investment compounds long-run losses.
- The monetary value placed on reducing climate-related death increases with income and population. In the *Combined* climate impacts scenario, lower income reduces willingness to pay for risk reduction, lowering 2100 valuation by about $100 billion relative to the reference.

Implications

USREP results reveal amplification and transmission of damages beyond what FrEDI alone captures. This highlights the value of using a GE approach—while PEs can assess direct physical impacts, GEs can assess how those shocks move through the economy, capturing both direct and indirect impacts. This lens helps rank adaptation options by their economy-wide payoff, and can be applied to *Accelerated Actions* to quantify avoided damages when warming is lower. Adaptation priorities indicated by the largest economy-wide effects identified by FrEDI-USREP include: protecting mobility by strengthening transport infrastructure against flooding and high tides, reducing climate risks to buildings in vulnerable areas, and improving heat resilience for workers. Taking such actions would reduce the economy-wide losses from climate change.

Author: Mei Yuan

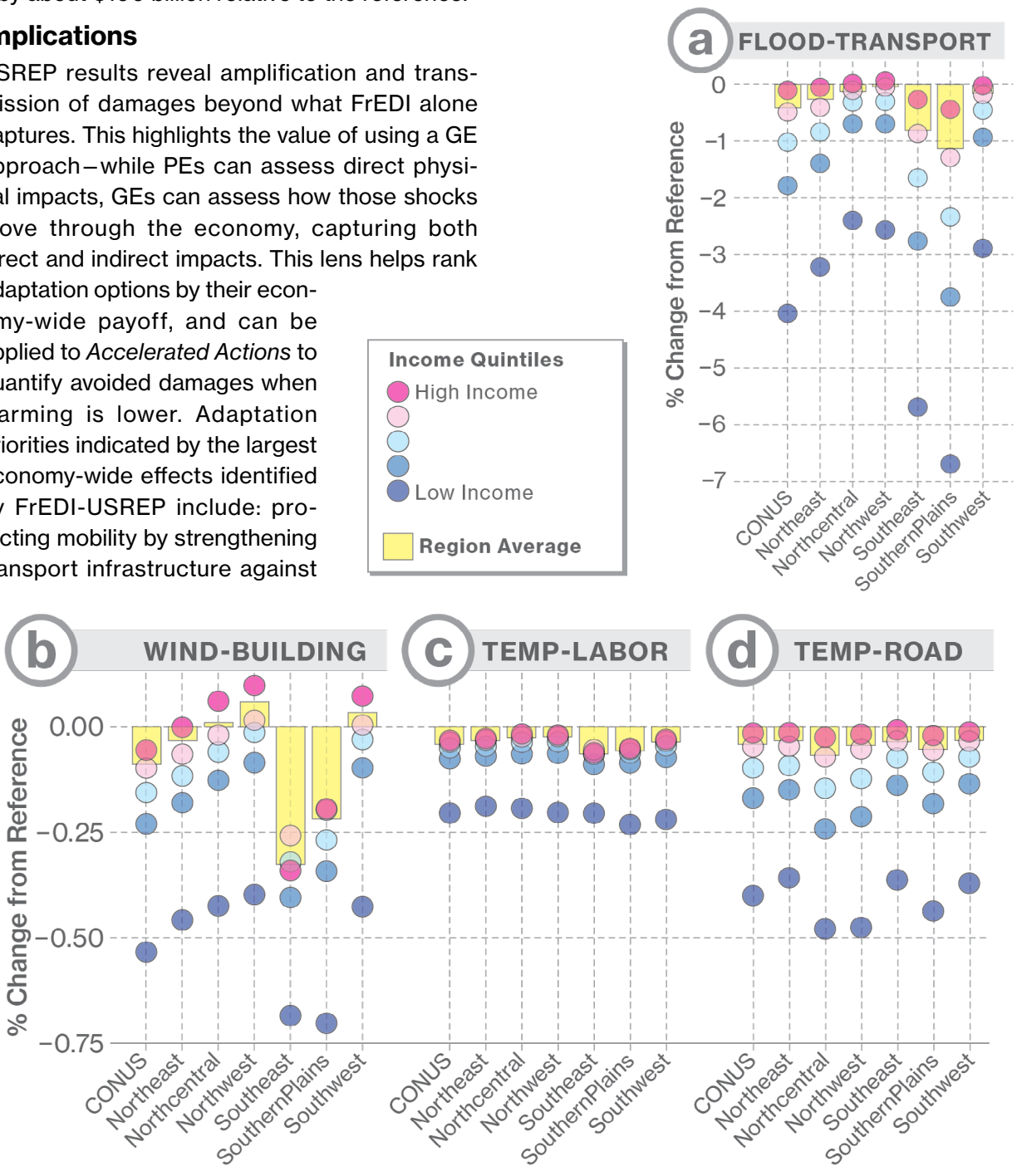


Fig. 31. Impacts on economic well-being by impact category, region, and income group in 2100. Panel (a) shows impacts in the *Flood-Transport* scenario. Panels (b-d) present results for the *Wind-Buildings, Temp-Labor,* and *Temp-Roads* scenarios. Note difference in scale between panels a and b-d.

Box 10. Protecting Agriculture from Adverse Climate Impacts

Demonstrated Potential of Irrigation and Agroforestry as Viable Strategies

The agriculture sector is highly vulnerable to climate impacts, which may reduce crop yields due to adverse growing conditions and unexpected losses from extreme events. Adaptation and mitigation strategies such as irrigation and agroforestry will be necessary to prevent and reduce harmful climate impacts on agricultural production.

Water use and land allocation are important adaptation and mitigation levers for addressing adverse weather and climate patterns. Changes in annual rainfall, decreases in water reservoir levels, and extreme weather events are likely to impact rainfed and irrigated crop production differently—and how farmers use water and land. To help decision-makers confront these challenges, we enhanced the MIT U.S. Regional Energy Policy (USREP) model by introducing multiple irrigated and rainfed crop production options in all U.S. regions and states, considering differences in costs and yields per hectare among crops and production systems, improving representation of water availability, and introducing capital expenses related to water supply (building on earlier CS3 advances[1,2]). Our approach captures several options for managing water and land, including expanding irrigated areas, improving irrigation methods, switching crops, increasing rainfed crop yields, and converting grasslands and forests to cropland.

In the U.S., approximately 18% of cropland was irrigated in 2022[3]. Using our enhanced USREP model, we performed a preliminary exploration of cropland impacts from adverse weather and climate shocks by 2050 in the Missouri River Basin, which covers Montana, Wyoming, Nebraska, North Dakota, South Dakota and Missouri (**Fig. 32**). The "Baseline" scenario assumes no changes in current weather and climate trends; the "Basin Shock" scenario assumes a decrease in water availability for irrigation by 13% by 2050; and the "Rainfed Shock" scenario assumes that rainfed crop yields decrease by 28% by 2050. We found that while production of all crops is negatively impacted in scenarios with adverse growing conditions, farmers can change land allocation to minimize impacts on production. When water for irrigation becomes scarce, they can expand rainfed agriculture; when rainfed crops are water-stressed, they can expand irrigation.

Agroforestry, which integrates trees with crops or livestock production, is another viable option for agriculture-based climate

1 Ledvina, K., *et al.* (2018). New Data for Representing Irrigated Agriculture in Economy-Wide Models. *Journal of Global Economic Analysis, 3*(1), 122-155 (doi:10.21642/JGEA.030103AF).

2 Winchester, N., *et al.* (2018). The Impact of Water Scarcity on Food, Bioenergy and Deforestation. *The Australian Journal of Agricultural and Resource Economics, 62*(3), 327-351 (doi:10.1111/1467-8489.12257).

3 Winters-Michaud, C.P. & Hrozencik, R.A. (2024). 2022 Census of Agriculture: Irrigated cropland reaches a 30-year low in 2022. Economic Research Service, U.S. Department of Agriculture. https://www.ers.usda.gov/data-products/charts-of-note/chart-detail?chartId=110247 [Accessed 4 Sept 2025]

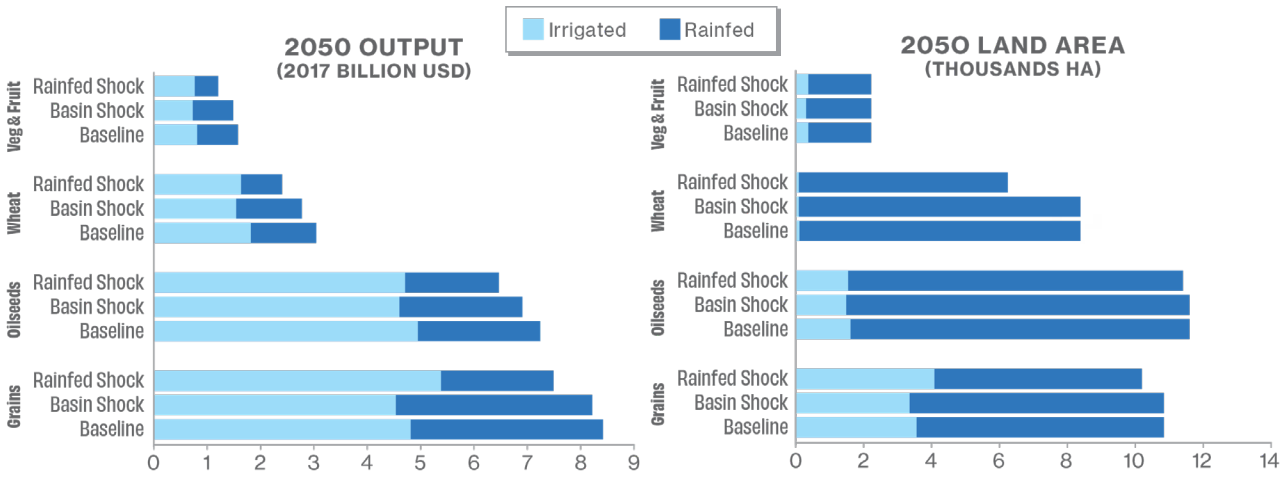


Fig. 32. Output (2017 billion USD) and land area (thousands ha) for grains, oilseeds, wheat, and vegetables and fruit in the Missouri River Basin in 2050 under a rainfed crop yield shock, a water basin shock and a "business as usual" baseline.

Implications for Sustainability • Agriculture

adaptation and mitigation. Viewed as a nature-based solution, agroforestry provides food production while enhancing carbon storage, biodiversity and adaptation to climate extremes. Using land-use records and historical sources covering the past century, we modeled and assessed the current carbon sequestration potential of a once-widespread silvoarable (cultivation of trees and crops on the same land) agroforestry practice in Northern Italy (**Fig. 33**). Our results suggest that larger afforestation allocations lead to higher sequestration potential. If the system was restored today, it could boost regional carbon sequestration up to 12%[4]. Achieving the same gain through afforestation would require converting one-quarter of the same area back to forests, since the carbon stock per hectare in those agroforestry systems is similar to the carbon stock of forests in a quarter of hectare.

Recent European Union legislation explicitly recognizes agroforestry as an eligible carbon farming practice. The potential economic opportunities are compelling. Silvoarable systems diversify income across food crops, timber, biomass and emerging carbon credits, while stabilizing yields and reducing reliance on external inputs. For farmers, this may translate into greater resilience and long-term profitability. For investors and policymakers, it may deliver measurable climate benefits that can be verified through robust data, certification frameworks and carbon markets. To evaluate the potential economic and environmental effects of agroforestry systems and corresponding EU legislation, we are incorporating agroforestry systems into our MIT Economic Projection and Policy Analysis (EPPA) model. This effort will allow us to test (a) if there is a clear path to integrate agroforestry strategies into market-based mechanisms, creating incentives that reward both climate action and agricultural productivity; and (b) if agroforestry represents a scalable investment opportunity for sustainable, multifunctional agriculture with durable co-benefits for farmers, investors and society.

Authors: Angelo Gurgel, Filippo Brandolini and Dominic White

4 Brandolini, F., *et al.* (2025). Data-driven scenario analysis supports the revival of historic silvoarable systems for carbon smart rural landscapes. *Scientific Reports*, in press (doi:10.1038/s41598-025-18950-7).

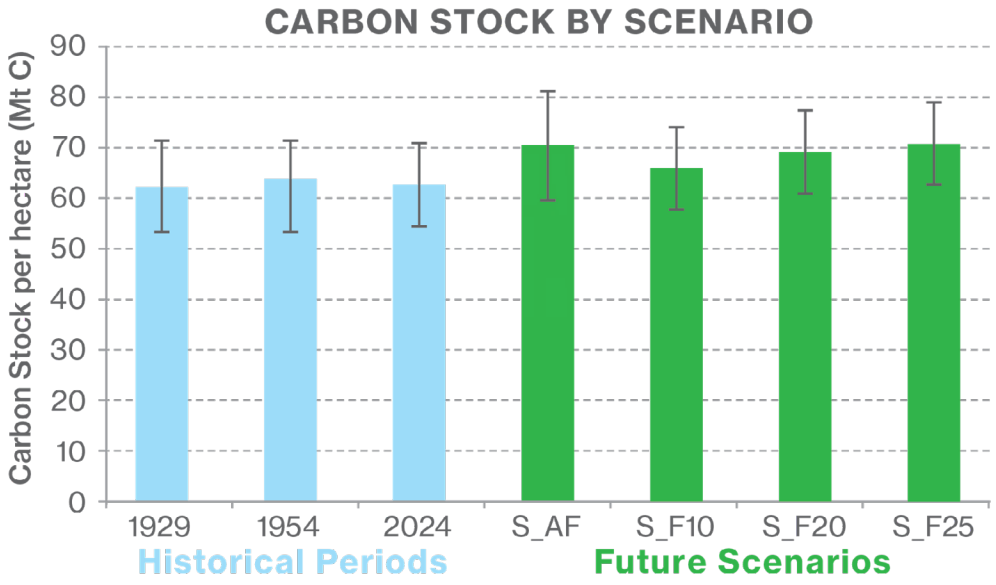


Fig. 33. Mean carbon stock (t C ha^{-1}) for historical land use periods and potential future land management scenarios in Northern Italy (Brandolini *et al.*, 2025). S_AF simluates full restoration of silvoarable agroforestry. S_F10, 20, and 25 simulate 10%, 20% and 25% of afforested area per hectare, respectively). Vertical bars represent 95% confidence intervals.

The available dataset for this analysis covers the years 1929 and 1954 (when agroforestry was widespread in Northern Italy) and 2024 (the most recent available data for comparison).

Co-Evolving Risks

Context

Physical and societal risks across natural, managed and built environments are becoming increasingly complex, interconnected and compounding. Addressing these multifaceted challenges requires informed decision-making supported by comprehensive analyses and model assessments. However, such efforts are often constrained by the significant computational and analytical resources they demand, making it impractical to conduct detailed modeling across all systems and scales. To address this challenge, we have developed the **System for the Triage of Risks from Environmental and Socioeconomic Stressors** (STRESS), a triage-based visualization and data-sharing platform designed to support efficient, data-driven risk assessment and prioritization. The STRESS platform integrates diverse observational and simulated datasets spanning socio-environmental systems, economics, demographics, health, climate, biodiversity and infrastructure.

Maps and data from this Outlook are available on the STRESS web interface—select the "world" region view.

Through the STRESS web interface (mst.mit.edu), users can generate and visualize customized risk indices derived from weighted combinations of selected metrics. Current metrics encompass land, water and energy systems; climate; biodiversity; demographics; environmental equity; and energy and transportation networks. This functionality enables users to explore various metrics and identify compounding "hotspots" of risks across various spatial domains (currently available at the U.S. and global level, with others under development). STRESS is an open-science resource, freely accessible to the broader community. We are committed to its continued development through an open, collaborative and interactive process that engages academic researchers, industry practitioners, policymakers and the public.

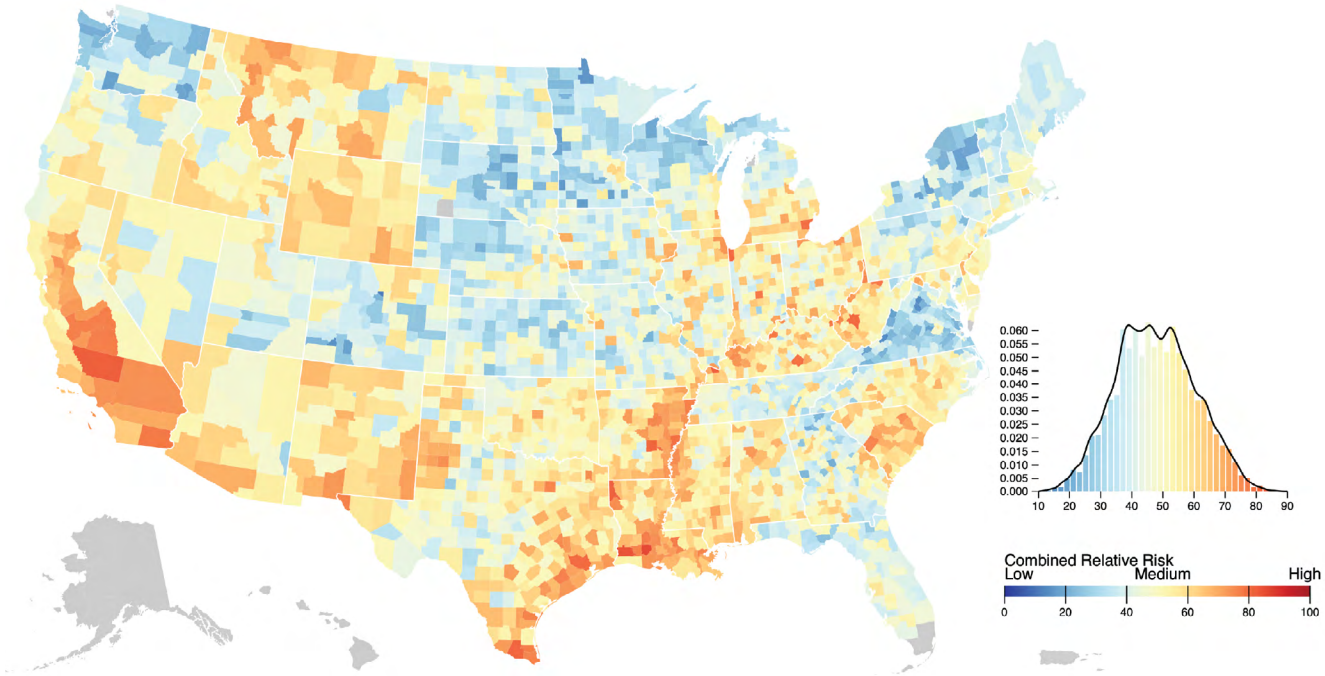


Fig. 34. Example of STRESS platform combinatory metric mapping. The combined effects (all equally weighted) of airborne particulate matter ($PM_{2.5}$), water availability and quality, fossil fuel employment, energy expenditure, poverty, and composite physical hazard (from weather extremes) is shown. The metric (unitless) indicates "hotspots" (highest values) where the percentile ranking of these selected factors predominantly coincide.

Implications for Sustainability • Co-Evolving Risks

Key Findings

The STRESS platform enables any user to make extensive, tailored selections of "combinatory metrics" to rapidly assess the regions in which multiple effects (specific to their concerns) predominantly coincide. As such, many possible combinations can be created. As a demonstration, we present a map (**Fig. 34**) that combines factors of air quality, water availability and quality, energy expenditure and production, poverty, and extreme weather risk. Several "hotspots" are located within the Southwest, the upper Midwest, the Deep South, Mountain West and South Atlantic. The strongest hotspots are within California and counties along the lower Mississippi River. In addition, several of the larger hotspot regions flank or are located within the greater Mississippi River Basin (MRB). Based on these factors, we apply more detailed and computationally rigorous models to focus on water impacts over the MRB (see **"Water" on page 27**), and apply advanced machine-learning methods to assess extreme precipitation over California (see **"Extreme Precipitation Events" on page 22**).

Implications

The STRESS "risk triage" platform has been developed as an efficient screening-level mapping tool to assess multiple hazards, impacts and risks, and to identify "hotspots" of these compounding factors. In addition, the platform provides a global mapping and data download for many of the model outputs featured in this report.

Author: C. Adam Schlosser



Appendix • Global projection data tables • *Current Trends*

This appendix contains projections for global economic growth, energy use, emissions and other variables to 2050. Similar tables for 18 regions of the world in the Outlook scenarios are available at https://cs3.mit.edu/Outlook2025.

	Units	2020	2025	2030	2035	2040	2045	2050
Economic Indicators								
GDP	bil 2023 $	100845.6	119809.3	136645.4	155869.4	177512.1	201550.9	225562.2
Consumption	bil 2023 $	56129.2	67222.4	77274.5	88035.9	99895.4	113214.7	126066.9
GDP growth	% / yr	1.1	3.5	2.7	2.7	2.6	2.6	2.3
Population	millions	7849.5	8195.1	8534.6	8852.9	9147.5	9413.3	9642.2
GDP per capita	2023 $	12847.4	14619.6	16010.8	17606.7	19405.5	21411.3	23393.2
GHG Emissions								
CO_2—fossil	Mt CO_2	33148.8	34442.6	35259.8	34443.4	32978.0	30767.5	28979.9
CO_2—industrial	Mt CO_2	1594.0	1791.6	1887.0	1955.3	2112.0	2206.2	2330.3
CH_4	Mt	350.7	355.5	358.7	353.5	351.8	355.0	358.0
N_2O	Mt	10.6	11.3	10.8	10.9	11.1	11.4	11.5
PFCs	kt CF_4	8.8	9.1	7.7	7.8	7.8	7.9	7.8
SF_6	kt	7.6	8.0	7.4	7.5	7.4	7.3	7.0
HFCs	kt HFC-134a	665.2	756.8	612.2	675.5	746.4	826.4	892.6
Total GHG net of Land Use	Mt CO_2e	48681.9	50660.9	51284.9	50520.0	49326.7	47487.3	46042.1
CO_2—land use change	Mt CO_2	2403.5	2052.9	1850.9	1651.5	1487.7	1335.7	1240.2
Primary Energy Use								
Wind	EJ	5.5	7.5	16.9	22.4	28.5	35.6	42.0
Solar	EJ	2.6	4.4	10.0	18.9	30.7	46.6	62.7
Bioenergy & other renewables	EJ	47.5	48.0	48.9	51.8	53.4	57.0	57.3
Hydro	EJ	15.9	17.0	17.3	18.1	19.1	19.5	19.9
Nuclear	EJ	31.0	34.4	38.7	42.4	46.7	52.2	55.9
Coal	EJ	159.0	157.8	160.5	151.8	139.9	128.2	115.7
Oil	EJ	176.2	194.6	198.8	202.9	200.6	195.4	189.2
Gas	EJ	137.7	146.9	157.9	166.2	169.8	166.4	170.5
Total Primary Energy Use	EJ	575.3	610.7	649.0	674.6	688.6	700.8	713.3
Electricity Production								
Wind	TWh	1525.1	2081.9	4694.7	6233.9	7918.5	9878.9	11677.2
Solar	TWh	715.9	1231.9	2769.8	5246.3	8524.7	12950.4	17422.2
Bioenergy & other renewables	TWh	483.2	533.7	553.9	639.3	735.5	890.1	1013.4
Hydro	TWh	4427.7	4722.6	4800.5	5030.1	5300.2	5427.2	5540.1
Nuclear	TWh	2839.3	3157.0	3550.0	3882.7	4279.0	4782.6	5127.6
Coal—no CCS	TWh	9606.9	9652.1	9645.8	8554.6	7616.8	6706.3	5630.8
Coal—CCS	TWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oil	TWh	836.7	743.8	883.3	989.9	940.7	802.3	770.9
Gas—no CCS	TWh	6301.0	7523.4	7939.4	8215.1	8449.7	8526.3	8658.9
Gas—CCS	TWh	0.0	0.0	0.0	0.0	0.0	13.0	29.6
Total Electricity Production	TWh	26735.9	29646.4	34837.3	38791.9	43765.1	49977.1	55870.8

Appendix • Global projection data tables • *Current Trends*

	Units	2020	2025	2030	2035	2040	2045	2050
Land Use								
Cropland	Mha	1507.4	1531.4	1548.8	1551.7	1566.1	1558.6	1549.2
Bioenergy	Mha	51.7	55.4	63.2	83.0	90.3	112.2	123.8
Pasture	Mha	1814.1	1819.0	1823.2	1817.2	1818.5	1815.4	1816.8
Managed forest	Mha	750.6	736.2	723.8	723.1	715.3	718.2	728.1
Natural grassland	Mha	1422.1	1415.9	1410.0	1404.2	1398.6	1393.2	1388.1
Natural forest	Mha	3321.8	3309.7	3298.7	3288.5	3279.0	3270.0	3261.7
Other	Mha	5141.8	5141.8	5141.8	5141.8	5141.8	5141.8	5141.8
Air Pollutant Emissions								
SO_2	Tg	84.9	76.8	70.6	62.3	54.5	48.2	42.1
NO_x	Tg	89.1	93.4	97.6	100.5	102.0	103.4	104.5
Ammonia	Tg	51.2	53.6	54.8	55.5	55.7	56.1	55.7
Volatile organic compounds	Tg	122.9	128.9	134.4	138.6	141.9	145.8	148.7
Black carbon	Tg	3.9	3.7	3.5	3.3	3.0	2.8	2.6
Organic particulates	Tg	10.0	9.3	8.6	7.9	7.2	6.6	6.0
Carbon monoxide	Tg	399.0	415.8	429.9	441.6	450.6	462.7	471.1
Agricultural and food outputs								
Crop	bil 2023 $	3564.3	4152.7	4659.0	5183.4	5697.5	6273.3	6751.0
Livestock	bil 2023 $	2359.6	2719.0	3024.4	3341.6	3661.8	4013.2	4305.8
Forest	bil 2023 $	449.8	560.3	675.2	802.8	939.7	1088.1	1233.2
Food	bil 2023 $	9308.1	10604.8	12030.7	13368.5	14749.7	16292.0	17830.8
Agricultural and food prices								
Crop	2025 price=1		1.0	1.0	1.0	1.1	1.1	1.1
Livestock	2025 price=1		1.0	1.0	1.0	1.1	1.1	1.1
Forest	2025 price=1		1.0	1.0	1.1	1.1	1.2	1.2
Food	2025 price=1		1.0	0.9	1.0	1.0	1.0	1.0
Energy prices								
Coal	2025 price=1		1.0	1.1	1.1	1.0	1.1	1.1
Oil	2025 price=1		1.0	1.0	1.0	1.0	1.0	1.0
Gas	2025 price=1		1.0	1.0	1.0	1.0	1.0	1.0
Electricity	2025 price=1		1.0	1.0	1.1	1.2	1.3	1.4

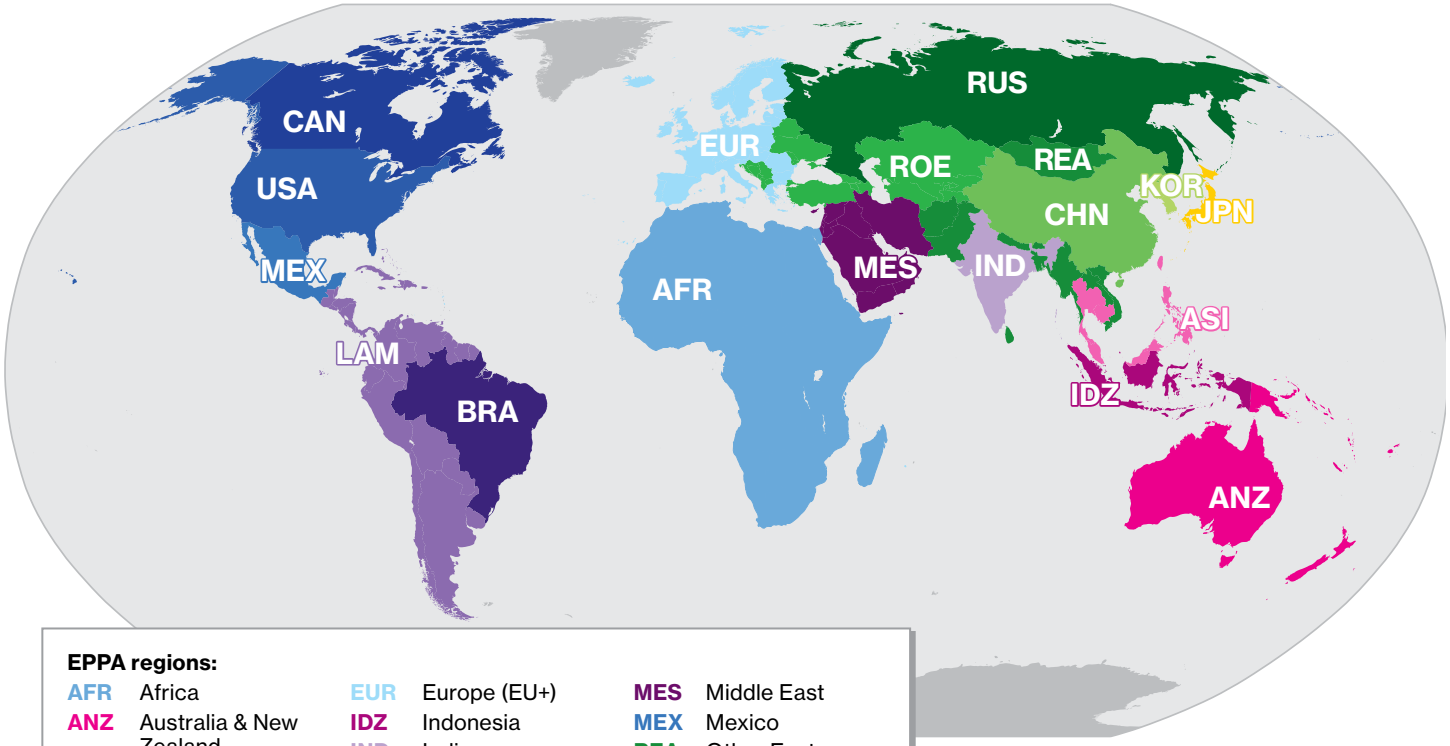
Appendix • Global projection data tables • *Accelerated Actions*

	Units	2020	2025	2030	2035	2040	2045	2050
Economic Indicators								
GDP	bil 2023 $	100845.6	119809.3	136030.2	154140.1	174285.3	196722.4	218016.5
Consumption	bil 2023 $	56129.2	67222.4	76959.8	87105.2	98149.1	110573.9	122066.3
GDP growth	% / yr	1.1	3.5	2.6	2.5	2.5	2.5	2.1
Population	millions	7849.5	8195.1	8534.6	8852.9	9147.5	9413.3	9642.2
GDP per capita	2023 $	12847.4	14619.6	15938.7	17411.3	19052.8	20898.4	22610.6
GHG Emissions								
CO_2—fossil	Mt CO_2	33148.8	34442.6	29588.9	23562.6	18547.8	14104.1	8893.1
CO_2—industrial	Mt CO_2	1594.0	1791.6	1539.6	1180.8	1169.5	1212.8	1175.0
CH_4	Mt	350.7	355.5	330.3	287.2	277.4	274.2	261.4
N_2O	Mt	10.6	11.3	10.4	10.1	10.1	10.2	10.0
PFCs	kt CF_4	8.8	9.1	7.6	7.5	7.6	7.6	7.3
SF_6	kt	7.6	8.0	7.4	7.3	7.2	7.1	6.7
HFCs	kt HFC-134a	665.2	756.8	593.6	654.7	722.6	796.0	849.7
Total GHG net of Land Use	Mt CO_2e	48681.9	50660.9	44319.7	36760.6	31561.4	27200.1	21615.9
CO_2—land use change	Mt CO_2	2403.5	2052.9	1556.9	811.9	322.3	141.6	14.3
Primary Energy Use								
Wind	EJ	5.5	7.5	18.9	27.5	40.6	48.9	65.4
Solar	EJ	2.6	4.4	10.6	20.1	39.2	62.5	86.5
Bioenergy & other renewables	EJ	47.5	48.0	51.6	57.1	65.1	66.7	65.2
Hydro	EJ	15.9	17.0	17.7	18.9	20.2	21.1	21.4
Nuclear	EJ	31.0	34.4	40.1	43.9	49.6	56.9	63.0
Coal	EJ	159.0	157.8	126.1	91.5	67.1	48.2	23.0
Oil	EJ	176.2	194.6	192.9	184.1	168.8	153.6	136.6
Gas	EJ	137.7	146.9	136.5	117.4	99.2	75.1	52.5
Total Primary Energy Use	EJ	575.3	610.7	594.2	560.6	549.7	533.0	513.7
Electricity Production								
Wind	TWh	1525.1	2081.9	5245.2	7640.6	11268.7	13575.5	18169.0
Solar	TWh	715.9	1231.9	2951.5	5588.2	10878.4	17365.4	24033.3
Bioenergy & other renewables	TWh	483.2	533.7	561.6	758.1	967.0	1251.3	1483.3
Hydro	TWh	4427.7	4722.6	4915.9	5259.2	5617.9	5860.9	5948.0
Nuclear	TWh	2839.3	3157.0	3675.1	4020.3	4544.1	5219.8	5778.8
Coal—no CCS	TWh	9606.9	9652.1	8586.4	6553.8	4744.8	3225.4	1125.7
Coal—CCS	TWh	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oil	TWh	836.7	743.8	777.7	719.8	577.9	407.0	192.2
Gas—no CCS	TWh	6301.0	7523.4	7652.9	7383.2	6356.5	4050.1	2569.2
Gas—CCS	TWh	0.0	0.0	40.1	97.1	204.2	393.7	748.1
Total Electricity Production	TWh	26735.9	29646.4	34406.4	38020.3	45159.5	51349.1	60047.4

Appendix • Global projection data tables • *Accelerated Actions*

	Units	2020	2025	2030	2035	2040	2045	2050
Land Use								
Cropland	Mha	1507.4	1531.4	1525.9	1522.4	1517.3	1512.2	1509.3
Bioenergy	Mha	51.7	55.4	85.8	115.8	147.0	161.6	167.6
Pasture	Mha	1814.1	1819.0	1824.1	1816.0	1809.4	1808.9	1810.3
Managed forest	Mha	750.6	736.2	721.5	713.7	702.2	699.9	700.8
Natural grassland	Mha	1422.1	1415.9	1410.0	1404.4	1398.9	1393.6	1388.7
Natural forest	Mha	3321.8	3309.7	3300.4	3295.3	3292.9	3291.4	3290.9
Other	Mha	5141.8	5141.8	5141.8	5141.8	5141.8	5141.8	5141.8
Air Pollutant Emissions								
SO_2	Tg	84.9	76.8	61.0	46.0	38.0	31.5	25.6
NO_x	Tg	89.1	93.4	89.9	83.8	84.0	82.8	80.8
Ammonia	Tg	51.2	53.6	54.4	54.5	54.5	54.6	53.5
Volatile organic compounds	Tg	122.9	128.9	128.4	126.7	127.3	128.7	128.4
Black carbon	Tg	3.9	3.7	3.3	3.0	2.8	2.6	2.3
Organic particulates	Tg	10.0	9.3	8.4	7.5	6.8	6.2	5.5
Carbon monoxide	Tg	399.0	415.8	414.1	409.9	415.8	422.3	423.3
Agricultural and food outputs								
Crop	bil 2023 $	3564.3	4152.7	4643.7	5128.2	5627.0	6167.4	6572.5
Livestock	bil 2023 $	2359.6	2719.0	3017.0	3307.3	3618.3	3942.2	4182.4
Forest	bil 2023 $	449.8	560.3	668.8	786.9	914.0	1051.7	1178.8
Food	bil 2023 $	9308.1	10604.8	12019.5	13299.2	14786.3	16309.6	17652.0
Agricultural and food prices								
Crop	2025 price=1		1.0	1.0	1.0	1.1	1.1	1.1
Livestock	2025 price=1		1.0	1.0	1.0	1.1	1.1	1.1
Forest	2025 price=1		1.0	1.0	1.1	1.1	1.1	1.2
Food	2025 price=1		1.0	0.9	1.0	1.0	1.0	1.0
Energy prices								
Coal	2025 price=1		1.0	1.0	0.9	0.8	0.8	0.7
Oil	2025 price=1		1.0	1.0	1.0	0.9	0.9	0.9
Gas	2025 price=1		1.0	1.0	1.0	1.0	0.9	0.9
Electricity	2025 price=1		1.0	1.1	1.3	1.4	1.5	1.8

Appendix • EPPA Regions



EPPA regions:

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

Regional data tables available at:
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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

Country	Region
Bolivia	LAM
Bosnia & 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

Country	Region
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

Continued on next page →

Appendix • EPPA Regions

Country	Region
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

Country	Region
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 Isl.	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
St. Helena	AFR
St. Kitts & Nevis	LAM
St. Lucia	LAM
St. Pierre & Miquelon	LAM
St. Vincent & Grenadines	LAM
Samoa	ANZ
San Marino	ROE
São Tomé & Príncipe	AFR

Country	Region
Saudi Arabia	MES
Senegal	AFR
Serbia & 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 & 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

Regional data tables available at:
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MIT Center for Sustainability Science and Strategy



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