MIT JOINT PROGRAM ON THE SCIENCE AND POLICY OF GLOBAL CHANGE

FOOD • WATER • ENERGY • CLIMATE
OUTLOOK
PERSPECTIVES FROM 2018

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

The Joint Program on the Science and Policy of Global Change is MIT's response to the research, analysis and communication challenges of global environmental change. We combine scientific research with policy analysis to provide independent, integrative assessments of the impacts of global change and how best to respond.

OUR RESEARCH MISSION

Our integrated team of natural and social scientists studies the interactions among human and Earth systems to provide a sound foundation of scientific knowledge to aid decision-makers in confronting future food, energy, water, climate, air pollution and other interwoven challenges.

THIS MISSION IS ACCOMPLISHED THROUGH:

- *Quantitative analyses of global changes and their social and environmental implications, achieved by employing and constantly improving an Integrated Global System Modeling (IGSM) framework;*
- *Independent assessments of potential responses to global risks through mitigation and adaptation measures;*
- *Outreach efforts to analysis groups, policymaking communities and the public; and*
- *Cultivating a new generation of researchers with the skills to tackle complex global challenges in the future.*

2018 Outlook: Exploring Global Changes

The ***2018 Food, Water, Energy and Climate Outlook*** continues a process, started in 2012 by the MIT Joint Program, of providing a periodic update on the direction the planet is heading in terms of economic growth and its implications for resource use and the environment. To obtain an integrated look at food, water, energy and climate, as well as the oceans, atmosphere and land that comprise the Earth system, we use the MIT Integrated Global System Modeling (IGSM) framework. Consisting primarily of the Economic Projection and Policy Analysis (EPPA) model and the MIT Earth System Model (MESM), the IGSM is a linked set of computer models developed by the MIT Joint Program to analyze interactions among human and Earth systems.

As in our last (2016) edition, this year's Outlook reports on projected effects of population and economic growth, technology improvements, climate policy and other factors on energy and land use, emissions and climate, and water and agriculture.

An important first step toward achieving stabilization of global average temperatures at reasonable cost is the Paris Agreement, in which nearly 200 countries committed to a wide range of initial climate actions aimed at achieving that goal. For this year's Outlook, we have invited guest contributors to offer perspectives on progress to date, and challenges and opportunities in fulfilling Paris climate pledges in several regions and countries around the globe. Recognizing the inadequacy of the short-term commitments to keep global warming below the long-term targets of 2°C or even 1.5°C, we explore emissions pathways consistent with these goals.

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About the 2018 Outlook

The *2018 Outlook* reflects a complete reevaluation of the economic, energy, land and water projections presented in the previous 2016 and 2015 editions. This year's report is based on a new version of our central economic model, the Economic Projection and Policy Analysis (EPPA) model, as well as revisions to our MIT Earth System Model (MESM). Updates and revisions reflect more recently available data. As with previous Outlooks, our intent is to represent as best we can existing energy and environmental policies and commitments, especially those under the Paris Agreement on climate change, assuming those commitments extend to the horizon of our modeling and reporting.

Since there are multiple changes in our assessment and representation of: (1) Paris Agreement pledges; (2) projections of economic and population growth; (3) underlying demand for resource-intensive products such as food, along with agricultural commodities; (4) technology costs; and (5) Earth-system response to changing emissions; it would be inappropriate to compare this Outlook with a previous edition and attribute differences in results to just one of these changes. Ascribing differences would require separating one set of changes from the others, and holding all the other things unchanged—a task that we have not undertaken.

Short-Term Paris Goals

Whether, and exactly how, countries will meet their Paris Agreement commitments remains mostly as unclear as it was in our previous evaluation. There are inevitable challenges in interpreting what existing commitments mean. Often the measures identified to date appear inadequate by themselves to meet the quantitative targets specified in each country's Nationally Determined Contribution (NDC). In that case we impose, in addition to the specific policies such as renewable energy goals or vehicle emissions standards, a broad cap on greenhouse gas (GHG) emissions in the country consistent with meeting the quantitative target. We have extended our analysis of Paris targets to all countries (previous editions only considered the NDCs of major emitters). The use of highly aggregated regions in our economic model requires us to approximate the aggregate impact of the varied policies of all countries within each region.

While the United States has announced an intention to withdraw from the Paris Agreement, in this Outlook we have continued to assume it will meet its target. The private sector and subnational entities (e.g. cities) worldwide have mounted a growing response to the U.S. announcement, but we follow the lead of the UN Framework Convention on Climate Change (UNFCCC) and assume that accounting of their goals and targets falls under country reporting. We thus do not estimate a separate effect of these commitments. Renewable energy investment has surged worldwide, and we have reflected that by imposing levels of renewable adoption as projected by the International Energy Agency. As a complement to our quantitative evaluation of the Paris Agreement pledges, experts on policy developments in various parts of the world provide their perspectives on how well key countries and regions are progressing in fulfilling their Paris pledges. Our goal in these is to indicate which countries appear to be more likely to fall short of their goals, or, in some cases, exceed them.

Long-Term Paris Goals

With expanded computational resources, we are now able to use our Integrated Global System Modeling (IGSM) framework to create large ensemble runs. This allows us to provide a full distribution of possible outcomes for a selected emissions scenario, given our uncertainty in climate response. In past Outlooks we approximated 90% confidence limits by running a case with median, high and low cli-

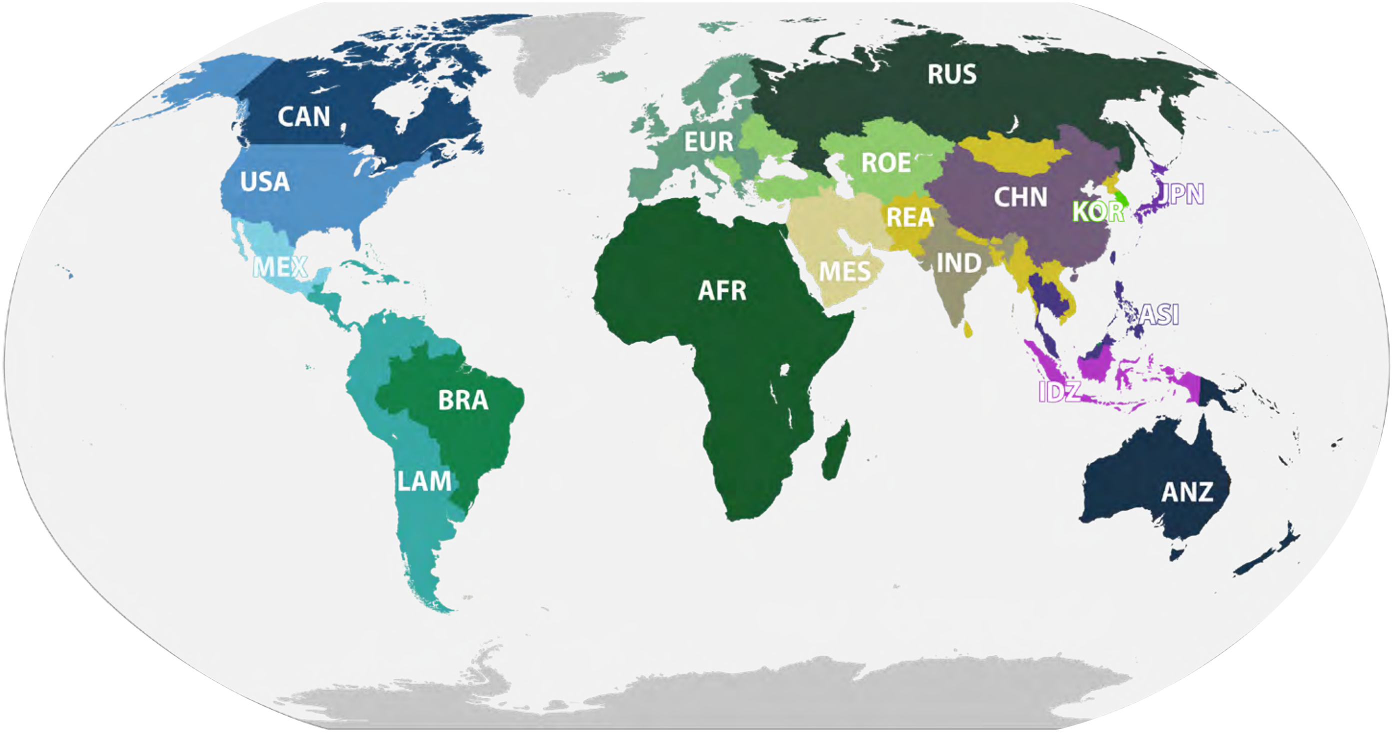

Figure 1. IGSM regions (see Appendix, p. 44 for details)

mate response.[1] By running a full ensemble, we can precisely delineate, conditional on our model and estimates of uncertainty, various confidence limits, encompassing the full range of outcomes including tails of the distribution.[2] This has allowed us to identify an emissions scenario consistent with "likely" remaining below a 2°C increase from the pre-industrial global mean surface temperature, and a scenario with a 50-50 chance of remaining below a 1.5°C increase.

Stabilization of global average temperature and GHG concentrations in the atmosphere is a long-term commitment that requires emissions reductions now—at least less increase in emissions—and then falling emissions that eventually get very low and tend toward zero in the long run. But since our mitigation focus in policy circles tends to be on what we are doing now and over the next 5–10–15 years, it is natural to ask: Is our near-term emissions trajectory "consistent" with stabilization at our desired goal? That, it turns out, depends critically on the available options for emissions abatement in the longer term—the second half of the century. We have added a section that takes our 2-degree emissions scenario and examines how different abatement opportunities in the second half of the century could give us more leeway in the near term.

Water and Crop Implications

We continue to highlight climate impacts on water resources and on agriculture and food. To complement some new quantitative results that suggest how climate change could affect commodity markets, we have invited a world-class expert on agricultural development to offer some thoughts on the global food situation.

We have also expanded our reporting in tables to include projected measures of agriculture and food output, and agriculture and energy prices. We are under no illusion that we could project the type of volatility we often see in prices in commodity markets, and our trend in projections may well prove to be wrong. However, in the end, the physical outcomes we are reporting—choices among different fuels, or pressure on deforestation—depend on the prices that are projected as part of our modeling exercise. Thus reporting these prices can help to explain our results.

Online tables are available for each of the individual regions of our EPPA model (see **Box 1** for regional classification details). Please note that all units of measurement are based on the metric system, and all economic values are reported in 2015 dollars.

Key Terms:

ASR	Assessment Sub-Region
CCS	Carbon Capture and Storage
CO_2-e	CO_2-equivalent
EPPA	MIT Economic Projection & Policy Analysis (model)
GHG	Greenhouse Gases
IGSM	Integrated Global System Modeling (framework)
IPCC	Interngovernmental Panel on Climate Change
LDC	Least Developed Countries
MESM	MIT Earth System Model
NDC	Nationally Determined Contribution
UNFCCC	United Nations Framework Convention on Climate Change
WRS	Water Resource System (model)
WSI	Water Stress Index

Units of Measurement:

°C	Degrees Celsius	**Mha**	Megahectares
EJ	Exajoules	**TWh**	Terawatt hours
Gt	Gigatons	**ppm**	Parts per million
Mt	Megaton		

Box 1.

Regional Classification Details

The IGSM modeling system used to generate the projections in this Outlook divides the global economy into 18 regions. These regions do not align exactly with the G20, the 20 largest economies of the world. For instance, South Africa, Argentina, Saudi Arabia and Turkey are G20 countries, but are also part of various regions that include countries not among the G20. Conversely, Norway, Switzerland, Iceland and Liechtenstein are not G20 members, but are combined with G20 members of the European Union, including France, Germany, Italy and the United Kingdom, as a single region. A full list of the countries included in each IGSM region is provided in the Appendix (p. 44) and supplementary projection tables are available online at: http://globalchange.mit.edu/Outlook2018. For the reporting in this Outlook, the regions are further aggregated into three broad groups: *Developed*, *Other G20* and *Rest of the World*.

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

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

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[1] Note that although the EPPA model has many uncertain parameters, these are not varied as in e.g. Webster *et al.* (2012). In the central scenario representing short-term Paris targets, uncertainty in underlying EPPA parameters in regions without absolute emissions caps would contribute to emissions uncertainty. In regions with absolute emissions caps and in the stabilization scenarios we consider, uncertainty in EPPA parameters would mostly contribute to uncertainty in costs, because emissions are prescribed. We do not represent uncertainty in policy implementation to meet emissions goals.

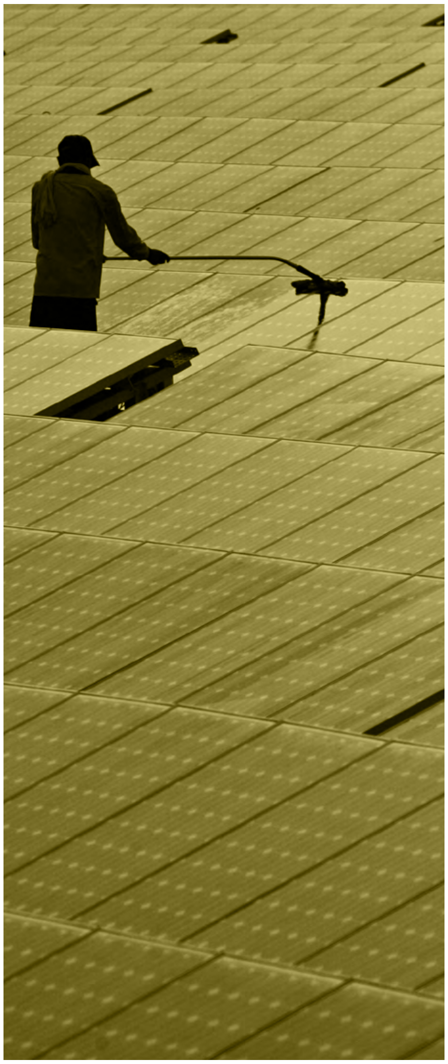
[2] There is, appropriately, much concern about extreme outcomes—long tails of the distribution that, while not highly likely, could be catastrophic. We run 400-member ensembles, so each outcome is 0.25% of the 400. However, since there is only one observation at that level, there's no statistical strength on the very extreme outcomes—the standard errors on those as limits are infinite. For any reasonable degree of statistical reliability, we should look at 10 or 20 in 400 occurrences—2.5 or 5%—which would give standard errors with some reasonable bounds. At this level, we are clearly not resolving really low-probability events—1 in 100, 1000 or 10,000—that if truly catastrophic would be something to avoid. Probably more important, our modeling system only includes processes and their responses for which we have some concrete evidence, yet there are speculative concerns—e.g. runaway climate change—or other Earth-system responses we have not even imagined. Hence, the information available about low-probability outcomes in our simulations is relatively limited—and of course all the outcomes in general are conditional on the modeling system we have, which is a highly parameterized approximation of the complex Earth system.

Key Findings

Energy and Land Use

Population and economic growth are projected to lead to continued increases in primary energy use, growth in the global vehicle stock, further electrification of the economy, and, with continued land productivity improvement, relatively modest changes in land use. While successful achievement of Paris Agreement pledges should begin a shift away from fossil fuels and temper potential rises in fossil fuel prices, it is likely to contribute to increasing global average electricity prices.

- We estimate that global primary energy use rises to about 730 exajoules (EJ) by 2050, up from about 550 EJ in 2015. The share of fossil energy (coal, oil, gas) drops from about 84% in 2015 to 78% by 2050. Primary energy use is projected to decline slightly to nearly flat in the *Developed* region, with the global increase coming from the *Other G20* and *Rest of the World* regions, despite continued reductions in energy intensity in all regions.
- The *Developed* and *Other G20* regions account for over 82% of global primary energy use in 2015. This drops gradually to 76% by 2050.
- The vehicle stock and fuel use in vehicles continue to increase in all regions through 2050, especially outside the *Developed* region despite our imposition of fuel economy standards in most regions as a likely measure countries will use to meet their Paris pledges. While private vehicle fuel use is a policy target in many countries, it generally accounts for less than 10% of primary energy use.
- Global electricity production rises substantially over the period 2015 to 2050, increasing by 62% compared with an increase in total primary energy production of 32%, indicating a continued trend of electrification of the economy. Renewables, natural gas, nuclear and bioenergy generation expand. Coal generation nearly disappears in the *Developed* region but remains about flat for the world as a whole, largely because of continued expansion of its use in China and India despite faster growth of other sources of generation in these countries.
- Compared with 2015, our projections show conversion of about 2.5% of natural forest area to crop and pasture land by 2050, with no further conversion through 2100. Slowing population growth, falling income elasticities of food demand, and continued yield improvements help to slow and halt conversion.
- We project about a 3% increase in cropland and an 8% increase in pasture between 2015 and 2050. Cropland then decreases through 2100, to about 2% less than in 2015. We also see a slight decline in pasture by 2100 compared with 2050, so that it is only 3% above the 2015 level.
- Despite an expansion of biomass energy of about 250% by 2050 (relative to 2015), land devoted to production of biomass for energy accounts for less than 1% of cropland that year.
- Global average fossil energy prices are projected to be nearly flat. Oil and gas prices rise by less than 10%, while coal prices fall by about 9%. Policies and measures that reduce demand for these fuels are partly responsible for these small price changes. Electricity prices rise gradually to about 31% above 2015 levels by 2050, in part because of polices used to meet Paris pledges but also because of gradual depreciation of older power plants that will be more expensive to replace.



Emissions and Climate

It is widely recognized that the near-term Paris pledges are inadequate by themselves to stabilize climate. On the assumption that Paris pledges are met and retained in the post-2030 period with further emissions reduction efforts, future emissions growth will come from the *Other G20* and developing countries, accelerating changes in global and regional temperatures, precipitation, sea-level rise and ocean acidification.

- Atmospheric concentrations of CO_2 exceeded 405 ppm as of April 2018. That of all long-lived GHGs, in CO_2-e, is now approaching 500 ppm.
- Annual emissions of the major greenhouse gases are projected to increase from 52 gigatons (Gt) CO_2-e in 2015 to just under 69 Gt by 2100 under our representation of current NDC commitments, extended through the century. Annual emissions are fairly flat through 2030, and they gradually increase after that as regions of the world that have not adopted absolute emissions constraints see emissions increases. The relative importance of different gases and sources remains about the same as today.
- The projected median increase in global mean surface temperature by 2100, above the 1861-1880 mean value, is 3.0°C—the 10 and 90% confidence limits of the distribution are 2.6 and 3.5°C.
- Median values for continental (North America, Europe, Asia, Australia, Africa, South America) average temperature increases vary from slightly below to slightly above 4°C by 2100. These show more warming than the global average because warming is generally greater over land than over the ocean. The continental projections also reflect the general result that warming is greater at the poles than at the equator, so regions with greater land areas toward the poles warm more.
- Other important projected changes in the Earth system include: a median ocean pH drop to 7.85 from a preindustrial level of 8.14 in 1861, with a 10 and 90% confidence range of 7.83 and 7.88; a median global precipitation increase of 0.18 mm/day, with a 10 and 90% range of 0.15 and 0.22 mm/day, relative to the 1861-1880 mean value; and median sea-level rise of 0.23 m in 2100, with a 10 and 90% range of 0.18 and 0.28 m, relative to the 1861-1880 mean value. The sea-level rise estimates include only that due to thermal expansion. Sea-level rise will likely be somewhat greater due to contributions from melting glaciers and ice sheets, and the committed level of sea-level rise is much greater even if temperature is stabilized because of the slow uptake of heat by the ocean that will continue for centuries.

Water and Agriculture

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

To develop our water projections for the period 2015-2050, we simulated water-stress measures developed for major river basins in the continental U.S. in a large ensemble to capture uncertainty in the Earth system.

- Results show a central tendency of increases in water stress by 2050 for much of the eastern half of the U.S. and the far west. The central tendency for the upper plains and lower western mountains shows a slight reduction in water stress.
- The full distribution of possible outcomes shows a marked asymmetry in the sign and corresponding strength of water-stress changes. For southern, southwest and western basins of the U.S., this asymmetry indicates a significant increase in water stress is more likely than a decrease.
- In northeastern basins no outcomes indicated a reduction in water stress. While this region currently experiences little water stress, and even with increases may not face the kind of severe water shortages typical of the southwest, it may need to prepare for unprecedented shortages.
- Our simulations include growth in demand for water from various water-using sectors, and so projected water stress can arise from growth in demand for water as well as reduced availability, or often a combination of these factors.
- MIT Joint Program Deputy Director C. Adam Schlosser offers a perspective on the looming water accessibility crisis the world will face with growing population and increasing water demands, calling on the need for risk assessment and response, while highlighting advances in modeling that can provide a more robust assessment of water risks.

Our base projections for agricultural production and prices for the 2015-2050 period reflect the effects of the Paris Agreement on energy and land-use decisions we used in our projections of country NDCs but do not consider the impacts on the sector of the unabated climate change we simulate. Guest contributor Mark Rosegrant (IFPRI) offers thoughts on transformative developments in agriculture, and Angelo Gurgel (Sao Paulo School of Economics, Brazil) provides some initial projections of how agricultural markets may be affected by climate, drawing on literature reviewed by the Intergovernmental Panel on Climate Change (IPCC).

- Our projections show that between 2015 and 2050 at the global level, the value of overall food production increases by about 130%, crop production increases by 75% and livestock production by 120%, incorporating recent econometric evidence on the relationship between population, income and food demand.
- While final demand for crops grows only about as fast as population growth, a projected shift to more meat consumption creates additional demand for crops for livestock feed.
- Food production grows faster than livestock and crop production because it includes value-added and other inputs used in producing food. A key expected transformation in agriculture is an increasing value-added component of food production as income rises, which Rosegrant identifies.
- Crop, livestock and forest-product prices rise at a moderate rate under an assumption of a 1% increase in land productivity in all land uses, less if the productivity growth assumption is 2% per year.
- Food prices from the food sector rise by less than 5% by 2050 relative to 2015, much less than the commodity prices because of the growing importance of the value-added component. Crop and livestock prices have a bigger direct impact in poorer countries where there is less food processing and more direct consumption from the crop and livestock sector.
- Simulating yield effects of climate change ranging from reductions of about 5 to 25% varying by crop, livestock type and region drawn from studies reviewed by the IPCC, Gurgel finds commodity price increases above baseline prices in 2050 without climate change of about 4 to 7% by 2050 for major crops, 25 to 30% for livestock and forestry products, and less than 5% for other crops and food. The differential regional changes in yields creates a comparative advantage for the *Developed* region, and a comparative disadvantage for the *Rest of the World* region, which includes many countries in the tropics where yields are expected to be more severely affected.

Meeting Short-Term Paris Commitments

Experts on policy developments in various parts of the world provide their perspectives on how well key countries and regions are progressing in fulfilling their Paris pledges. They report on some bright prospects, including expectations that China may exceed its commitments and that India is on a course to meet its goals. But they also observe a number of dark clouds, from U.S. climate policy developments to the increasing likelihood that financing to assist the least developed countries in sustainable development will not be forthcoming at the levels needed.

- Kenneth Kimmel (Union of Concerned Scientists) suggests that a combination of dark clouds, red flags, silver linings and Hail Mary passes cast great doubt over whether the U.S. will meet its Paris pledge to reduce greenhouse gas emissions by 26–28% below 2005 levels by 2025.
- Michael Mehling (MIT Center for Energy and Environmental Policy Research (CEEPR) and University of Strathclyde) notes that while Europe has successfully met earlier targets and styled itself as a climate leader, more recently, emissions have risen with growing energy demand and industrial output, jeopardizing achievement of the 2030 pledge and the long-term target of an 80–95% reduction by 2050 below 1990 levels.
- Valerie Karplus (MIT Sloan School of Management) finds several promising signs that China will fulfill and even exceed its Paris pledge for 2030, which includes: (1) to reach peak CO_2 emissions, (2) to increase its non-fossil share of primary energy consumption to 20%, (3) to reduce CO_2 intensity by 60–65% relative to 2005 levels, and (4) to increase its forest stock by 4.5 billion cubic meters compared to 2005.
- Karplus and Arun Singh (ETH Zurich) suggest that India's CO_2 emissions performance since 2015 indicates that the nation can meet and even beat its Paris ambitions. Progress over the next 15 years will hinge on the pace of energy-demand expansion, system-level challenges to integrating renewables, and the prominence of clean energy in the national development narrative.
- Niven Winchester (Motu Economic and Public Policy Research, and the MIT Joint Program) writes that the new South Korean president is considered a pragmatist, and his government is moving more aggressively on climate policy than the previous administration. Winchester cites a study estimating that a $90/ton emissions price would be needed for Korea to meet its 2030 Paris pledge, likely higher than in most other regions of the world, illustrating challenges of emissions reductions in middle-income countries with relatively rapid economic growth.
- Mustafa Babiker (Saudi Aramco, and the MIT Joint Program) points out that the Middle East/North Africa (MENA) region is particularly vulnerable to the physical effects of climate change and the socio-economic impacts of climate mitigation efforts due to its deep economic dependency on hydrocarbon resources. NDCs for countries in the region are broadly framed in the context of sustainable development and climate adaptation goals, with some commitments contingent on international financial support. Emissions reductions efforts are focused on increased deployment of renewables with a variety of initiatives that would support that development, especially in some of the countries with more aggressive efforts.
- Achala Abeysinghe (International Institute for Environment and Development, and legal and strategic advisor to the Chair of the Least Developed Countries (LDCs) Group for the UNFCCC), writes that despite the unquestionable determination of the LDCs to develop sustainably, mitigate GHG emissions, adapt to climate change, and address loss and damage, they lack the resources and tools to effectively implement their NDCs. Global support has lagged far behind what is required, primarily due to a lack of climate finance. The adequacy, predictability and sustainability of global climate finance have become questionable.

Long-Term Climate Stabilization Goals

The Paris Agreement established more precise long-term temperature targets than previous climate pacts by specifying the need to keep "aggregate emissions pathways consistent with holding the increase in global average temperature well below 2°C above preindustrial levels" and further adding the goal of "pursuing efforts to limit the temperature increase to 1.5°C." We find that those targets remain technically achievable, but in general require much deeper near-term reductions than those embodied in the NDCs agreed upon in Paris. Because the Earth-system response to increased greenhouse gases is uncertain, we compared emissions paths that stay below 2°C with a 50-50 (i.e. 50%) chance to those that had a 2-in-3 (i.e. 67%) chance of staying below that level, and interpreted the 1.5°C aspiration with a 50-50 chance, with or without a temporary overshoot of that target. For these long-term targets, we applied globally uniform carbon pricing that increased over time, starting in either 2020 or 2030 to determine whether a 10-year delay in going beyond Paris NDCs rendered the long-term goal unattainable.

- Making deeper cuts immediately (2020) rather than as a next step in the Paris process (waiting until 2030) would lower the carbon prices needed to achieve long-term goals, and reduce the need for unproven options to achieve zero or negative emissions after 2050. We estimate that achieving 2°C with a 50-50 chance would require an $85/ton carbon dioxide-equivalent (CO_2-e) carbon price if started in 2020, or $122 if delayed until 2030 (in 2015 dollars). Achieving 2°C with a 2-in-3 chance would require carbon prices of $109 in 2020 or $139 if started in 2030.
- We estimate that achieving the 1.5°C aspiration with a 50-50 chance would require a carbon price of $130 in 2020. Allowing an overshoot would mean less drastic measures in the near term but would rely on negative emissions technology in the second half of the century.
- Given the representation of future technology in our model, we would deem the Paris pledges as inconsistent with even the 2°C with a 50-50 chance, because the carbon price path that balances short and long-term costs requires a very sharp drop in emissions, compared to the Paris goal, when put in place in 2030. It is hard to imagine a political process that would deliver this as a global policy, and if implemented, the sharp drop would leave stranded assets and likely cause other economic disruptions.
- If we can develop reasonable cost options to get to zero emissions after 2050 in sectors where we currently do not see easy solutions, extensively take advantage of carbon sequestration in forests and soils, or advance negative emissions technologies such as bioenergy with carbon capture and storage (CCS), then the Paris path to 2030 is less clearly inconsistent with the 2°C goal. This would allow for a smoother transition but put a heavy bet on these unproven options.

Box 2 summarizes the major updates and changes in the *2018 Outlook*. The remaining report describes the details behind these broad conclusions.

Box 2.

New in the 2018 Outlook

Updated Modeling Framework

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

Expert Perspectives

We provide perspectives from experts around the world on progress toward meeting Paris pledges, recent trends in greenhouse gas concentrations, and developments in agriculture and water resources.

Expanded Reporting

We now report energy and agriculture commodity prices and projected changes in food, crop and livestock demand.

Emissions & Energy Scenarios for Stabilization

We expand our evaluation of climate stabilization scenarios to include some that are likely to keep the global temperature rise below 2°C, and others that are consistent with a 1.5°C target.

A Revised Look at the Implications of Paris Agreement Pledges

We extend our analysis of Paris Agreement pledges to include commitments of most of the countries of the world, whereas in previous Outlooks we only considered commitments of major emitters.

Risk Assessment

We include results of large MESM ensembles to provide increased resolution on the risks of climate change that reflect underlying uncertainty in the Earth-system response to higher levels of greenhouse gases and other climate forcers.

Charting the Earth's Future

In this section we describe the major drivers of global change, including the Nationally Determined Contributions (NDCs) under the Paris Agreement, and how we have implemented them in our Integrated Global System Modeling (IGSM) framework. We describe implications for energy and land use, greenhouse gas (GHG) emissions and climate, and food and water.

Our baseline projection assumes that the Paris commitments, which formally extend only through 2025 or 2030, are met by all regions, and are held in place through the end of the century. Of course, some countries may not meet their commitments; others may exceed their targets; and in general, the expectation under the UN Framework Convention on Climate Change (UNFCCC) is that new commitments will be made for the post-2030 period.

Drivers of Global Change

Key drivers of global change are population and economic growth. We adopt a central estimate of population growth from the UN (UN, 2017). These most recent projections have the global population growing to about 9.8 billion by 2050, and to 11.2 billion by 2100. This is up by about 220 million in 2050 and 330 million in 2100 compared with the population projections we used in our previous Outlook. The biggest increases are in Africa; our EPPA model's Rest of Asia region; a mix of Asian countries (excluding China, India, South Korea, Japan, Thailand, Singapore and Indonesia); and, to a lesser extent, the Middle East, Russia, Mexico, Australia/New Zealand and Canada. Together those regions contribute to a nearly 0.5 billion increase by 2100. Offsetting these increases were lower population forecasts for China, India, Europe, the U.S., our East Asia region, Indonesia, Brazil, our other Latin America region and South Korea, for a total decrease of about 160 million. With some exceptions, those revised projections amplify somewhat the contrast between the combined *Other G20* and *Developed* regions, where populations are stabilizing and then gradually declining, and the *Rest of the World*, where populations are continuing to increase (**Figure 2**). The main exceptions are Russia, Australia/New Zealand and Canada, with Japan essentially unchanged from the previous estimate.

In our baseline projection, we target near-term/historical GDP growth to data and forecasts of the International Monetary Fund (IMF, 2018), and then include an estimate of long-term productivity growth for each underlying EPPA region. The result is world GDP annual growth rate of about 2.6% through 2050, slowing to 1.9% for the period 2050–2100 (**Figure 3**). Growth is slower in the *Developed* region, rising at an annual rate of about 1.9% through 2050 and slowing to 1.5% in the second half of the century. The *Other G20* grows the fastest—3.7% per year through 2050, and 2.1% per year thereafter. The *Rest of the World* grows at 3.2% per year before slowing to 2.5% per year. The *Developed* region accounts for about 63% of world GDP in 2015, falling to just under 49% by 2050 and down to just under 40% by 2100.

These trends in population and GDP increase pressure on natural resources including energy, water and land. The pressure is offset in part by technological change that increases yields and reduces energy

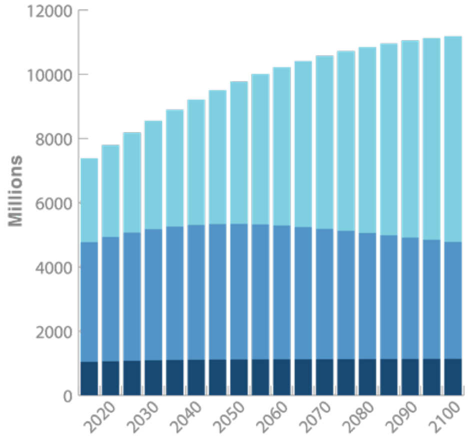


Figure 2. World Population

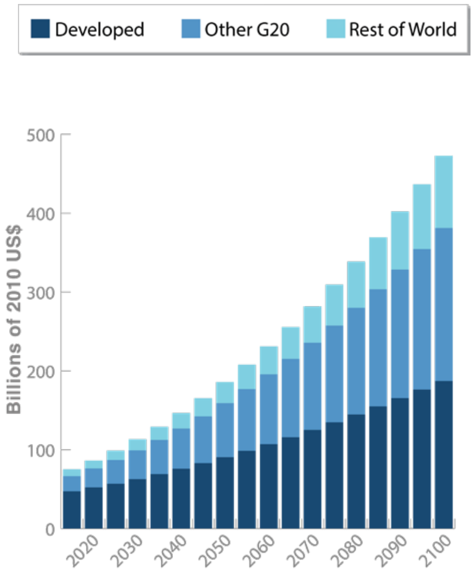


Figure 3. World GDP

use per unit of production activity, and other broad-scale efficiency improvements.

Also playing a key role in driving global change are energy and land-use policies, which could significantly modify the effects of population and economic growth. We incorporate existing policies and measures in our projections, focusing on the emissions targets and policies identified in countries' NDCs submitted under the Paris Agreement. To represent in our modeling system the approximate effect of policies and measures on emissions levels requires considerable interpretation (**Box 3**). Ultimately we express these effects as emissions reductions or intensity reductions expected by 2030 in terms of carbon dioxide equivalent (CO_2-e). These various policies and measures and our conversion to specific targets are detailed in Box 3.

We achieve these targets through a mix of policies and measures. These include matching renewable energy expansion in all regions as projected by the International Energy Agency (IEA, 2017); matching nuclear expansion for our Middle East, Russia, China and India regions as in the IEA (2017); imposing vehicle efficiency improvements for regions where these are on the books or proposed; and where these are insufficient to meet the targets, imposing additional emissions caps to assure that the assessed targets are met.

At the time our previous analysis was completed, as reported in our 2015 and 2016 Outlooks, we only had access to Intended Nationally Determined Contributions (INDCs) submitted in the lead-up to the 21st Conference of the Parties (COP21) in Paris.

Box 3.

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

We assess the NDCs of countries under the Paris Agreement, implementing them at the country/region level of the EPPA model. Many countries describe emissions reduction targets relative to an absolute (ABS) level of emissions defined by an historical level such as 2005. Europe and Russia continue to use 1990 as the base year. Other countries such as China and India describe targets based on emissions intensity (INT). For countries with NDCs included within larger EPPA regions, we have assessed how their targets would affect emissions for the region as a whole relative (REL) to business-as-usual (BAU), and summarize the combined effects in the final column of the table as a percentage reduction of CO_2-e from the identified base for each country/region, or in terms of energy intensity reductions for regions that have chosen emissions intensity as a goal.

Table 1. Conversion of policies and measures in NDCs to specific targets.

	NDC[1]			CO_2-e 2005 Mt or t-CO_2/\$1000[2]	Other Features	Expected CO_2-e[4]
	Type	Base	Reduction			
USA	ABS	2005	2025: 26–28%	6220	-	25%[5]
EUR	ABS	1990	2030: 40%	5370 (1990)	Electricity 27% renewables by 2040.	40%
CAN	ABS	2005	2030: 30%	789	Mainly land use/forestry with 18% industrial reduction.	25%
JPN	ABS	2005	2030: 25%	1260	2.5% land-use change/forestry. Electricity 20–22% nuclear; 9% solar/wind; also biomass. Assumes internationally transferred mitigation outcomes. Target = 1.04b tCO_2-e.	20%[6]
ANZ	ABS	2005	2030: 26–28%	596	-	20%[7]
BRA	ABS	2005	2025: 37%	2.19	Primary energy 45% renewables by 2030; land-use change/ forestry down 41% 2005–2012.	35%
CHN	CO_2 INT	2005	2030: 60–65%	2.00 (INT)	CO_2-only NDC[3]; 2030 CO_2 peak; primary energy 20% non-fossil.	55%
KOR	REL	BAU	2030: 37%	-	Policies & measures on renewables and autos (no detail).	25%
IND	INT	2005	2030: 30–36%	1.17 (INT)	2.5–3.0 b tCO_2 from forests. Electricity 40% non-fossil. Assumes unspecified financial assistance.	30%
IDZ	REL	BAU	2030: 29%	-	Role of land use/forestry (63% of current emissions) unclear; Industrial emissions increase.	30%
MEX	REL	BAU	2030: 25%	-	22% of CO_2; 51% of black carbon; 40% INT 2013–2030.	25%
RUS	ABS	1990	2030: 25–30%	3530 (1990)	Reduction subject to "maximum accounting" from forests.	32%
ASI	REL	BAU	-	-	Malaysia 45% INT; Philippines 70% BAU; Thailand 20% BAU; Singapore 36% ABS.	10%
AFR	REL	BAU	-	-	Nigeria 45% BAU; South Africa 20–80% increase ABS; limited info on other regions.	5%
MES	REL	BAU	-	-	Saudi & Kuwait actions only; Iran 15% BAU; UAE non-GHG actions.	10%
LAM	REL	BAU	-	-	Argentina 15% BAU; Chile 35% INT; Peru 20% BAU; Colombia 20% BAU.	10%
REA	REL	BAU	-	-	Bangladesh 5% BAU; Pakistan reduction after unspecified peak; Sri Lanka 7% BAU; Myanmar & Nepal misc. actions.	10%
ROE	REL	BAU	-	-	Azerbaijan 13% BAU; Kazakhstan 15% 1990; Turkey 21% BAU; Ukraine 40% BAU.	10%

1 Sources include UNFCCC (2016) and CAT (2016).

2 In 2007 US$.

3 With discount to account for other gases.

4 Percentage applies to the base in column 3, given the type of target in column 2.

5 Based on assessments by Greenblatt and Wei (2016), Larsen *et al.* (2016) and Vine (2016).

6 Discounts Internationally Transferred Mitigation Outcomes (ITMOs) and nuclear expectations.

7 Expectation discounted by political reversals in Australia.

Now all NDCs have been submitted and the Paris Agreement entered into force. We thus assume targets will be met, and extend our assessment to more regions. There remains considerable room for interpretation of what many pledges mean, as well as exactly how they will be implemented. The targets described in Box 3 show our best attempt to come up with a comprehensive evaluation of the Paris Agreement that can be represented within our modeling framework.

While the mechanisms for implementing the Paris Agreement often remain unspecified, there has been a focus on improving vehicle efficiency standards. Many countries have adopted or proposed standards for light-duty vehicles. We have thus implemented vehicle standards as part of the set of policy measures applied to achieve the Paris targets. While there has been less attention to vehicle standards for heavy-duty vehicles, some discussion has now emerged on what these might look like. The specific targets we have applied in various regions are shown in **Box 4**.

Box 4.

Vehicle Efficiency Standards

Standards for light-duty vehicles that we have applied are shown in **Figure 4**. Commercial transport is a bigger source of emissions than light-duty vehicles in most regions. The standards we have imposed on heavy-duty vehicles (commercial transportation in our model) are shown in **Figure 5**.

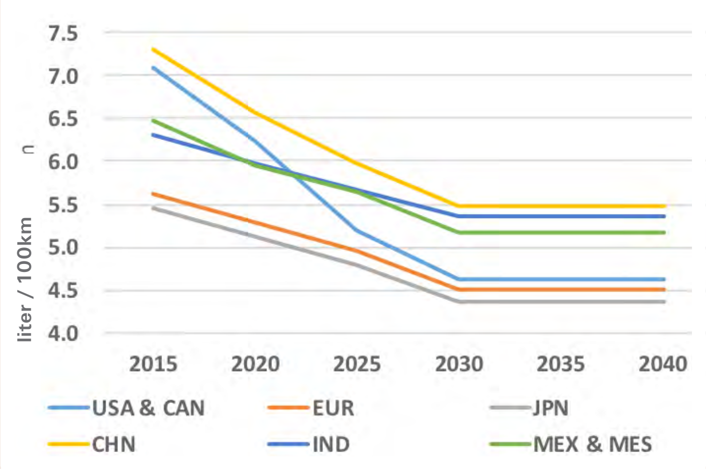


Figure 4. Efficiency standards for light duty vehicles to meet the first NDCs

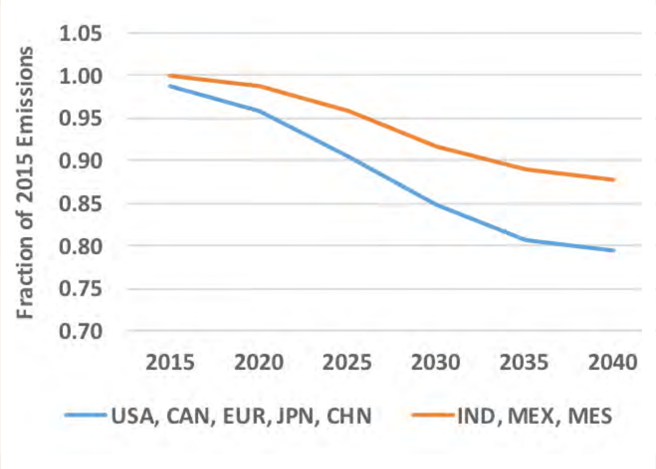


Figure 5. Reduction of energy use in commercial transport

Energy and Land Use

Primary Energy Use through 2050

We estimate that global primary energy use rises to about 730 exajoules (EJ) by 2050, up from about 550 EJ in 2015 (**Figure 6**). The share of fossil energy (coal, oil, gas) drops from about 84% in 2015 to 78% by 2050. Coal use drops by about 2 EJ, and its share of primary energy falls from about 29% to 22%. Oil and gas use continue to increase, and their share of primary energy also increases slightly (from 55% to 56%), partly offsetting the decline in the share of coal. Bioenergy increases by more than 60% and wind & solar by more than six times. There is a wide range of policy incentives for wind & solar across the world, ranging from feed-in tariffs to tax credits to renewable portfolio standards. These incentives often vary among different jurisdictions within our EPPA regions (see Box 1, p. 3). This may occur, for example, among different European countries, or among different U.S. states. For that reason we cannot explicitly represent these various policy incentives, and instead have used regional quantity targets that rely heavily on International Energy Agency projections. Without these targets we would generally see less of an increase in the expansion of wind and solar power.

The *Developed* and *Other G20* regions account for over 75% of global primary energy use through 2050. The share drops from 82% in 2015 to 76% in 2050. However, the trends are much different between these two large regions (**Figure 7**). In the *Developed* region, total primary energy use, already somewhat lower than the *Other G20* in 2015 at about 200 EJ compared with ~255 EJ, drops to just over 185 EJ by 2050. In contrast, the *Other G20* primary energy use rises to about 373 EJ. Coal use virtually disappears in the *Developed* region, while oil use declines by about 9 EJ and gas use increases by about 15 EJ. Trends in nuclear and wind & solar electricity are nearly offsetting, with nuclear declining by 13 EJ (as many older reactors are retired) and wind & solar collectively increasing by 15 EJ.[3] In contrast, in the *Other G20*, coal use increases slowly by about 17 EJ, gas use is about flat, oil use increases by 58%, nuclear generation triples and wind & solar increase 13-fold. These countries are characterized by moderately high per capita GDP, rapid growth and large populations, so most supply sources are increasing along with energy demand. Restrained gas use is largely an issue of a lack of existing infrastructure, access and relative prices.

In **Figure 8** we change the reported scale to give greater detail on the *Rest of the World*, and two of the largest countries included in the *Other G20*, China and India. China is the dominant primary energy user, consuming on order of five times as much as India, and more than all the 150+ countries in the *Rest of the World* combined. We project that coal use in China peaks in 2030, with oil use continuing to increase. However, thanks to a substantial increase in wind & solar (13-fold) and nuclear (8-fold), the fossil share of primary energy drops from 88 to 71% between 2015 and 2050. India has an aggressive policy to expand solar, and our projection has wind & solar increasing by 17-fold, but it remains a small share of primary energy

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[3] We report each of nuclear, hydro and renewable electric generation as its "primary-equivalent," the fossil fuel that would be needed to generate an equivalent amount of electricity.

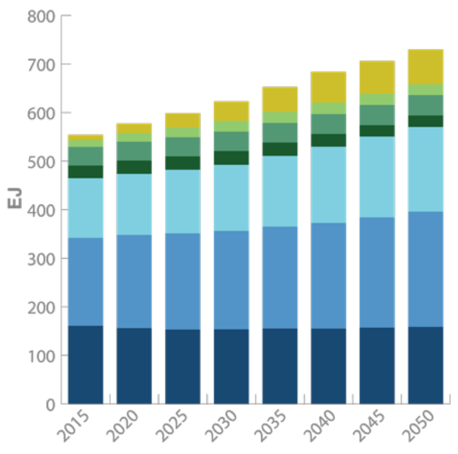

Figure 6. Global Energy Use (exajoules)

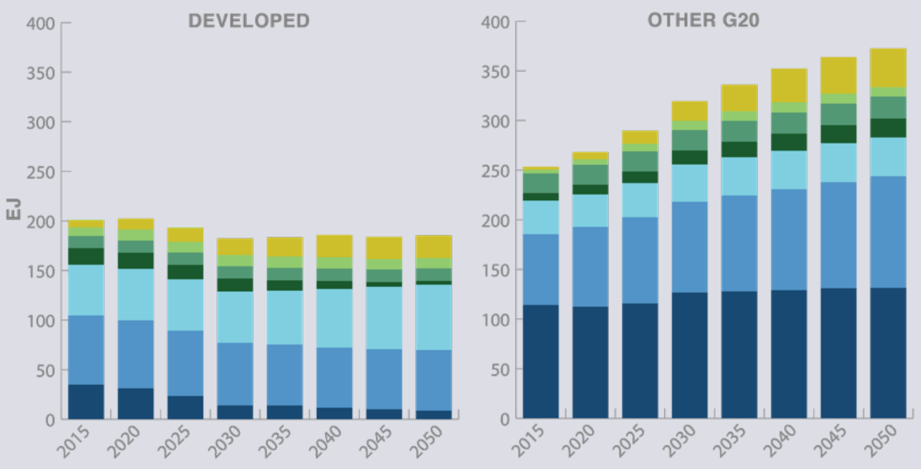

Figure 7. Energy use by major group. *Developed* (left) and *Other G20* (right)

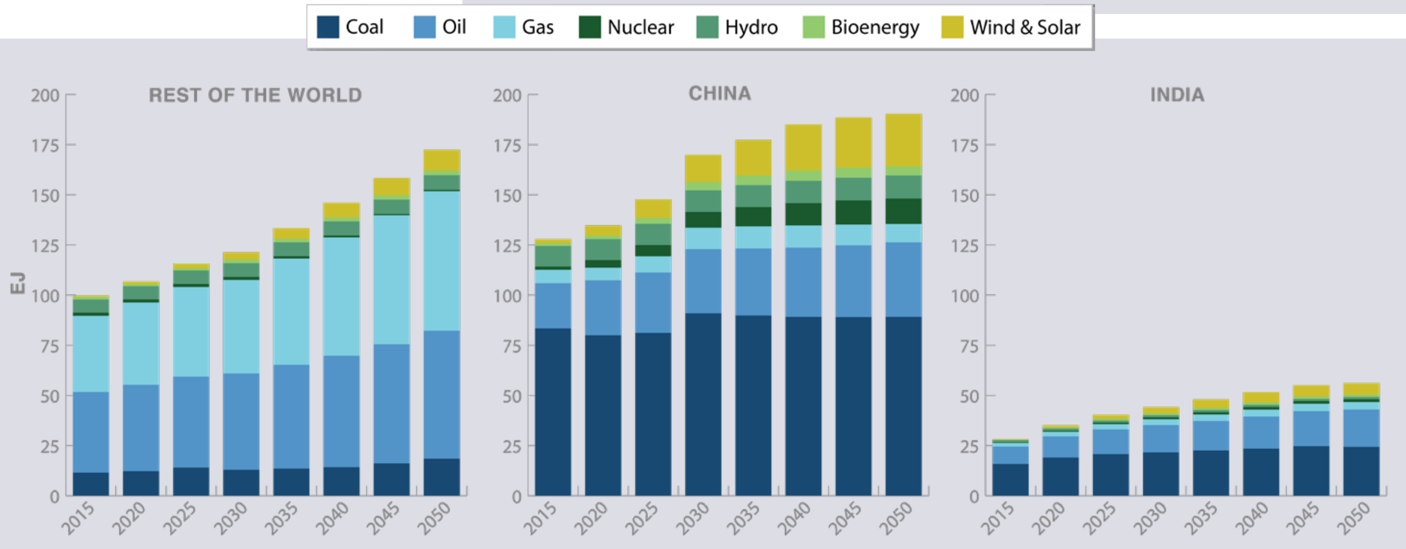

Figure 8. Energy use by major group. *Rest of the World* (left), China (center) and India (right)

use, with fossil energy accounting for 93% in 2015, dropping to 83% by 2050.

Primary energy use grows rapidly in the *Rest of the World*, rising by 73% in a region where many people currently do not have access to commercial energy. Most of the energy use draws on oil and gas, as coal resources are limited in most of these countries. Wind & solar increase by over 17-fold, but from a small level, and so contribute only 6% of primary energy use by 2050. Non-commercial biomass is a large contributor to current energy use in many of these countries, but we do not separately account for it.

Regional Energy Intensity Improvements

The changes in the energy intensity of GDP in each region stem from a complex combination of factors. One major factor is the projection of ongoing autonomous energy efficiency improvement. Historically there has been a long-term trend toward reducing energy intensity per dollar of constant GDP, especially among more developed regions, that is not explained by rising energy prices. This trend is less pronounced among countries that are far less developed. One explanation is a gradual structural change as per capita GDP rises. Among very poor countries, a large share of energy may be provided by non-commercial sources such as firewood, dung and draft animals that we do not explicitly account for as an energy input. Thus, as development proceeds at this early stage, a shift from non-commercial to commercial energy sources is likely to show up as an increase in energy intensity (possibly partly offsetting other trends). Early stages of development may also involve large investment in infrastructure (e.g. roads, rail, buildings) that require energy-intensive industry such as iron, steel and cement. However, as development proceeds, there is a general shift to less energy-intensive manufacturing and services. Individual country intensities may also be strongly affected depending on whether they produce energy-intensive goods domestically and for export, or instead import them. For example, various estimates show China producing and exporting relatively energy-intensive goods to Europe and the U.S., thus increasing China's energy intensity and decreasing that of Europe and the U.S. (compared to the case where they produce these goods themselves). Finally, technological change that reduces energy use per unit of output (and as result lowers the cost of production) is likely a contributor to these trends.

In general, one should not compare absolute levels of energy intensity across countries based on the reporting data we show (**Figure 9**). Our data reports energy intensity in exojoules (EJ) divided by GDP in U.S. 2015 dollars at 2007 market exchange rates. Market exchange rates can be highly variable and hence affect, from one year

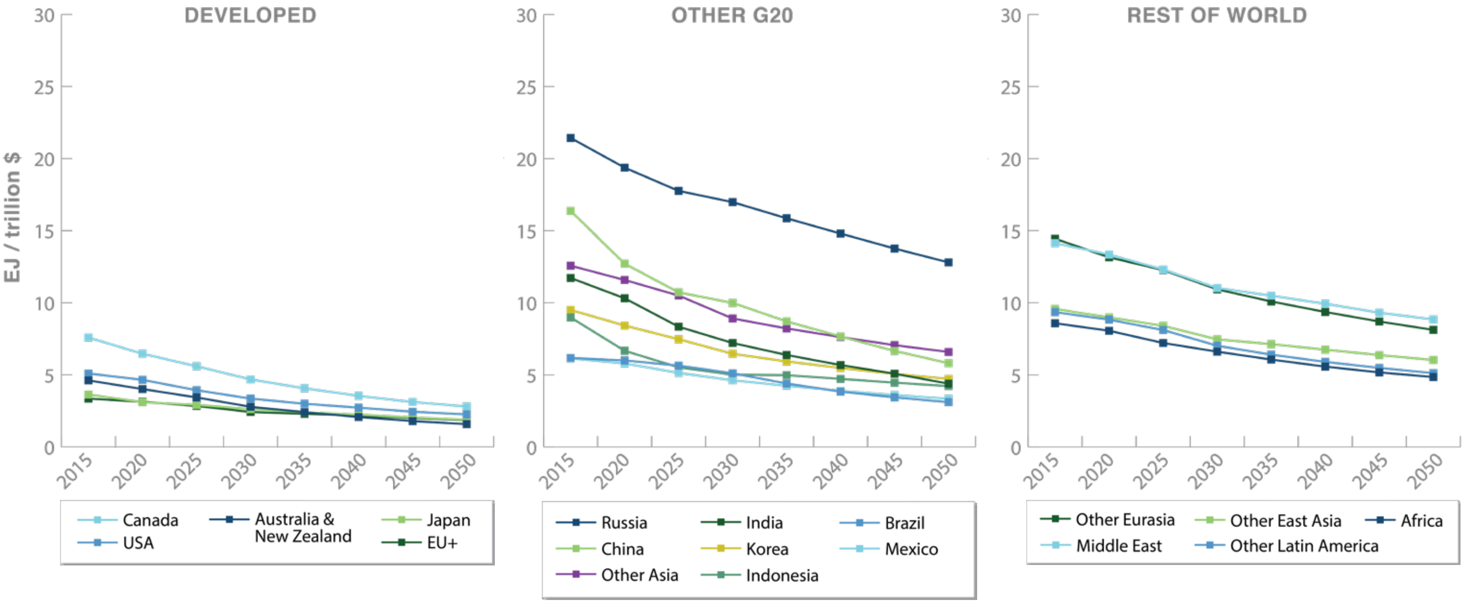

Figure 9. Energy Intensity (EJ/trillion US 2007$) for *Developed*, *Other G20* and *Rest of the World* regions

to the next, the apparent relative intensity of different economies. For a cross-country comparison of absolute levels, a conversion to a purchasing power parity index would reduce some of this year-to-year apparent variation. Moreover, to make really sensible comparisons, one should likely look at very well-defined production sectors and compare technical efficiency, and then explain other differences as due to exports and imports, and the broader sectoral composition of consumption.

As indicated in Figure 9, our results focus on the trends over time, showing general reduction in energy intensity in all regional economies. While there are poorer countries where some of the factors that could increase energy intensity pertain (e.g. switching from non-commercial sources, infrastructure development), these do not dominate any of the regional aggregations we model. The factors that lead to reductions in energy intensity include structural change, technological change, energy and climate policies, and rising electricity prices; as we will see later, fossil fuel prices are generally flat in our projections. The rate of economic growth also has a strong effect—faster growth means higher investment, and so a greater portion of the capital stock incorporates newer, more energy-efficient technology.

While the overall trends among regions are similar, there are some differences. The most rapidly improving countries and regions are Australia/New Zealand (ANZ), China, India and Canada, all improving at an annual rate of around 3%. The U.S., Brazil, Indonesia and Korea are improving at rates of 2 to 2.3% per year. Most other areas are improving at around 1.6 to 1.9% per year, with Other East Asia and the Middle East being the slowest at 1.3% per year. This area includes some poorer countries likely affected by forces related to early stages of development.

Private Vehicles and Transportation

Climate mitigation policy has focused significantly on efficiency and fuels for private vehicles, and, indeed, our analysis shows the global vehicle stock growing fairly rapidly (**Figure 10**)—increasing by nearly 61% by 2050 relative to 2015. It is growing in each of the three aggregate regions reported in the figure, but relatively slower in the *Developed* region, which accounted for almost 55% of the vehicle stock in 2015. Slower growth than other regions results in that share falling to 46% by 2050. Meanwhile, the *Other G20*'s share grows from 32% to 37%, while the *Rest of the World*'s share grows from 14% to 17%. The rapid growth in the *Other G20* reflects the fact that incomes rise to a level where more and more people in these countries can afford cars. There is also accelerating growth of vehicle ownership in

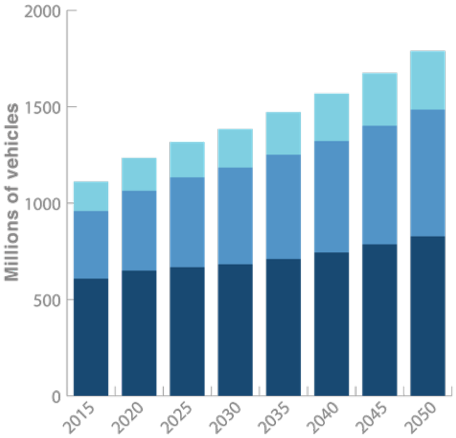

Figure 10. World private vehicle stock (cars and light trucks)

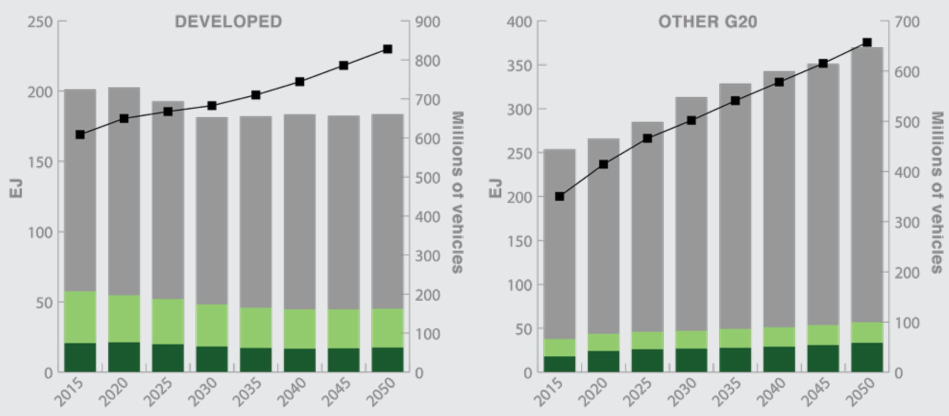

Figure 11. Transport energy use and private vehicles stock. *Developed* (left) and *Other G20* (right)

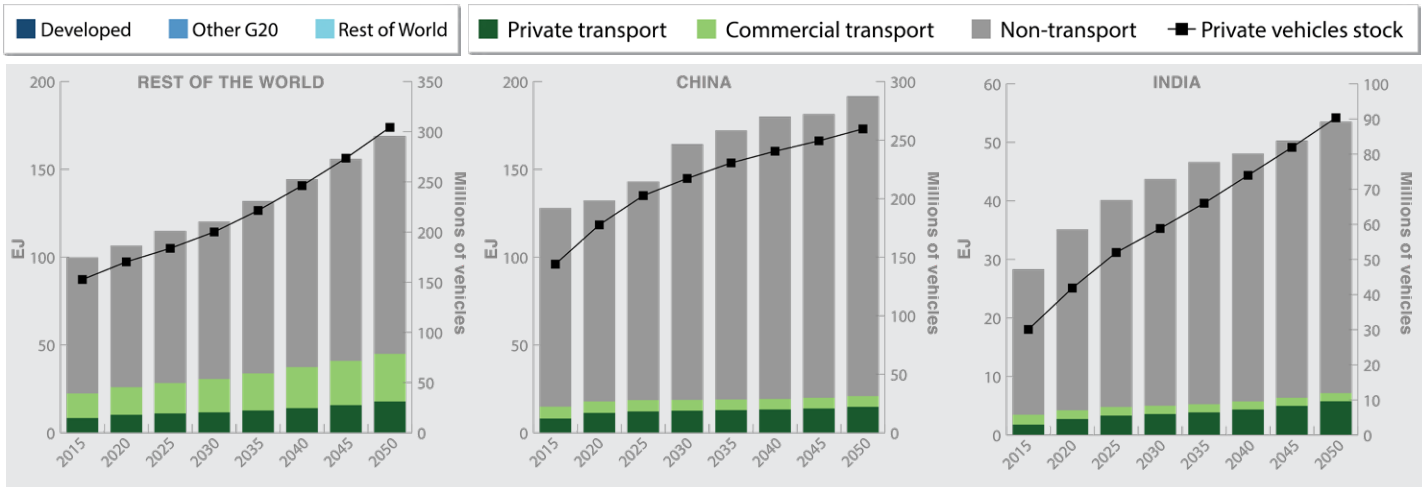

Figure 12. Transport energy use and private vehicles stock. *Rest of the World* (left), China (center) and India (right)

the *Rest of the World* as incomes there continue to rise.

The various requirements on vehicles that many countries are pursuing to meet their Paris climate targets both raise the cost of vehicles and slightly restrain their growth. While policy analysts have focused heavily on vehicle efficiency as a means of achieving GHG emissions targets, in general, private vehicles account for a relatively small share of primary energy use (and, as a result, of GHG emissions). While overall transport fuel use was about 29% of primary energy use in *Developed* countries, private vehicle consumption was just 10% in 2015. Obviously to meet economy-wide emissions targets, a focus on commercial transportation and other sectoral fuel use is needed. That said, the various policies on vehicles, if implemented as we represent them, are effective in restraining growth in fuel use.

As shown in **Figure 11**, while the stock of vehicles in *Developed* countries grows by about 36% over the period 2015-2050, fuel use by those vehicles declines, and the share of primary use also falls slightly to about 9.5%. In the *Other G20*, the number of vehicles almost doubles by 2050, with fuel use up by about 86%. In this region, private vehicle fuel use grows from about 7% of primary energy demand in 2015 to 9% in 2050. Notably, overall primary energy demand is growing in the *Other G20*, and so the growing share is of a growing total. While the pattern is different among these countries, with some, such as South Korea, adopting stringent fuel economy standards, overall there is less focus on vehicle standards as we interpret the NDCs of these countries. Of course, exactly how targets are implemented remains uncertain, so this result could change. A notable result of these somewhat different trends is that fuel use by private vehicles in the *Other G20*, currently about 10% less than in the *Developed* region, is about double that in the *Developed* region by 2050.

Looking toward the *Rest of the World* (**Figure 12**), the overall pattern in terms of fuel use by private and commercial transportation, and the share of the total primary energy use, is not that different from what we see in other regions. However, the overall scale in terms of number of vehicles and fuel and primary energy use is much smaller—despite the large population and geographic area this region represents. For example, the population of the *Rest of the World* is more than 2.5 times that of the *Developed* region by 2050, but the number of vehicles is about 25%, fuel use by private vehicles about 47%, and overall primary energy use about 39% that in the *Developed* region. Between 2015 and 2050, overall primary energy use increases by 1.7 times in our projections, and the share of that used by private vehicles increases from 8 to 11%, and that of commercial vehicles increases from 14 to 16%.

Transportation patterns in China and India—part of the G20 but highlighted here because of the large fraction of the world's population these countries represent—are similar in some ways but different in others. Both have a much smaller share of primary energy devoted to commercial transportation (5.3 and 6% for China and India in 2015, respectively). This may be due to the high energy-intensity of the economies as much as to differences in commercial transportation. In both cases these shares are declining in our projections (to 3.2 and 2.6% by 2050, respectively, for China and India), while those of private vehicles are increasing (to about 8 and 11% by 2050 for China and India, respectively). Obvious in Figure 12 is that in India, the overall scale of total primary energy use, number of vehicles, and fuel use in vehicles is much smaller than in China, despite similar population levels.

Electricity Production

Global electricity production rises substantially over the period 2015 to 2050, increasing by 62% compared with an increase in primary energy production of 32%. This reflects a continued increase in the electrification of the global economy, with some additional incentive in those regions with climate policies that penalize direct fuel use. Coal use in power production is virtually flat over the entire period. Wind and solar generation increases 7-fold, bioenergy by 2.5 times and hydro by 21% (**Figure 13**). The combined share of these renewables in electricity production rises from about 22% in 2015 to 37% in 2050. Nuclear remains flat. Oil-fired generation is negligible and decreases further. Gas generation also expands considerably, more than doubling, making it roughly tied with coal as the largest sources of power generation in the world.

As noted earlier, a wide range of different mechanisms support wind and solar, from feed-in tariffs to renewables requirements to tax incentives, which vary among individual countries and jurisdictions within countries. Rather than attempting to independently assess how all of these mechanisms would work, we instead approximate them with renewable portfolio standard (RPS)-type requirements that produce levels of wind and solar in each of our EPPA regions that approximately match projections in the International Energy Agency (IEA) Energy Outlook.

The *Developed* and *Other G20* regions produced (and used) about 85% of global electricity in 2015 in roughly equal amounts (**Figure 14**). However, production in the *Developed* region is projected to increase by only about 11% by 2050, while that in the *Other G20* increases by 114% between 2015 and 2050. Also evident from these projections, the near flat amount of electricity from coal generation at the global level results from essentially phasing out coal in the *Developed* region while coal use continues to increase in the *Other G20*. Both regions see a substantial increase in wind & solar, but different trends for nuclear. In the *Other G20*, nuclear generation expands, while in the *Developed* region it is mostly phased out as aging reactors are retired. The *Developed* region relies heavily on gas generation to replace coal and nuclear where the expansion of renewables falls short. The phase-out of coal (and expansion of renewables) is strongly driven by greenhouse gas policies in these regions, with gas filling in as the least costly option. These dynamics vary within the different regions that make up our *Developed* region.

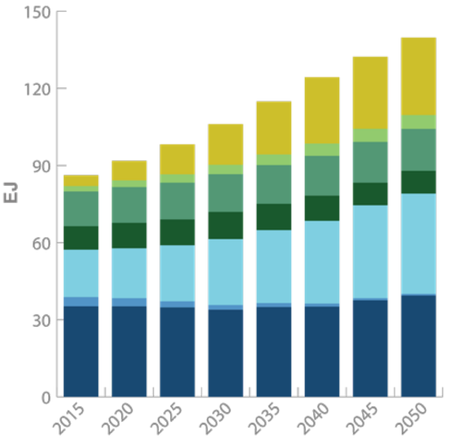

Figure 13. World electricity production (exajoules)

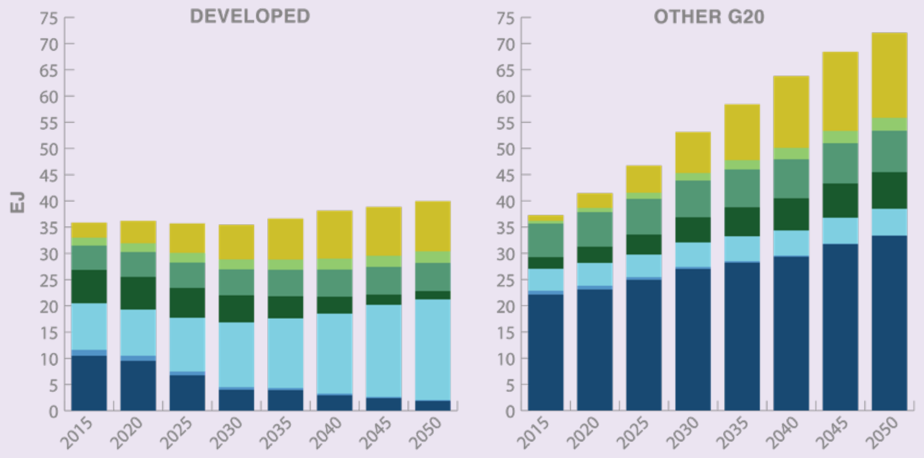

Figure 14. Electricity production by major group. *Developed* (left) and *Other G20* (right)

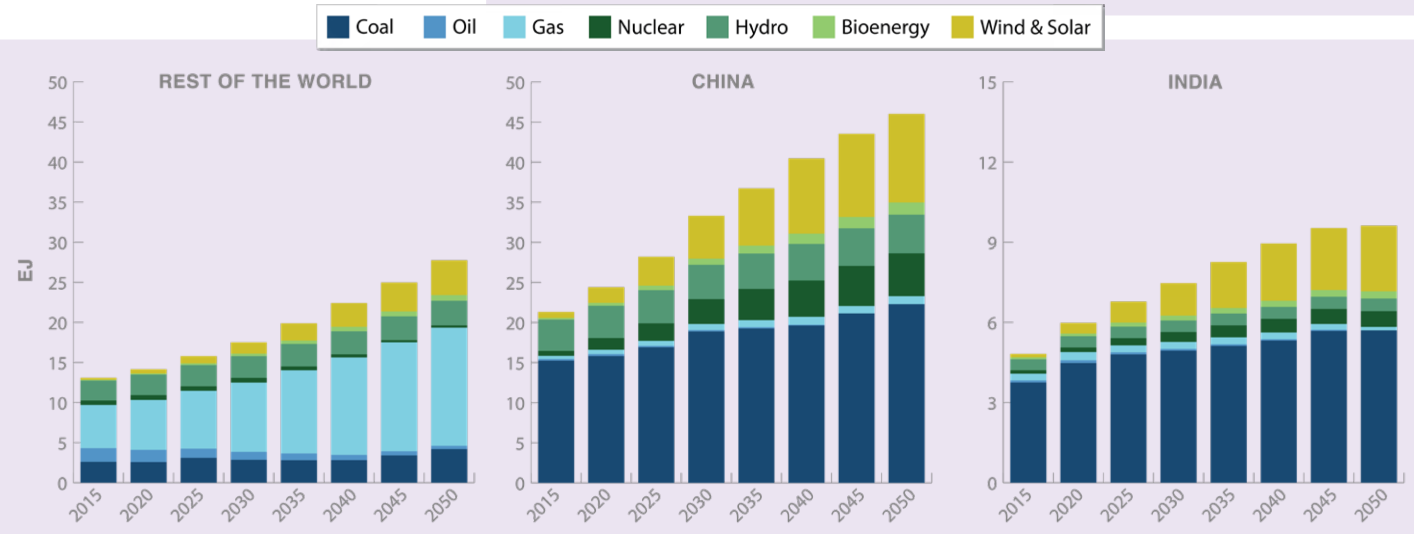

Figure 15. Electricity production by major group. *Rest of the World* (left), China (center) and India (right)

Electricity generation and use is also growing rapidly in the *Rest of the World* region (**Figure 15**), more than doubling between 2015 and 2050. However, even in 2015 electricity use in this region accounted for only about 15% of the global total. Our projections have coal generation increasing by about 60%, gas generation almost tripling and hydro increasing by 24% by 2050. The most rapidly increasing sources of generation are wind and solar (18-fold, though from a small base) and bioenergy (7-fold). Nuclear is currently small, and our projections have it remaining so, with oil generation disappearing. Even though gas generation expansion is not as rapid as for some other sources, it is the dominant share of generation in 2050 (about 53%).

Separating China and India from the *Other G20* shows that China alone is, and continues in our projection to be, a bigger electricity consumer than all of the *Rest of the World* countries combined. Electricity production in India is much lower, and unlike the *Other G20* generally and the *Rest of the World*, its electricity use begins to level off. The most likely reason is higher electricity prices, driven by its fairly strong commitment to solar power; wind and solar reach 26% of electricity production by 2050. China's commitment to decarbonization also shows a dramatic shift in generation toward generally zero-carbon sources (including nuclear, wind and solar, hydro and, to a lesser extent, bioelectricity), collectively accounting for about 49% of generation by 2050. Most of the rest comes from coal, which despite the tremendous expansion of other sources, increases by about 46% by 2050. As noted earlier, total coal use in China peaks earlier—China is one of the few countries where there is substantial use of coal outside of the power sector. In most other countries, as goes the fate of coal generation, so goes the fate of total coal use.

Land-Use Change

We have significantly improved the land-use change component of our EPPA model, allowing us to more consistently project integrated scenarios of energy, agriculture, emissions, climate and land use. Overall, we project that global land use is fairly stable over the century, with limited deforestation of natural forests (**Figure 16**). Compared with 2015, our projections show a loss of about 2.5% of natural forest area by 2050, and no further decline through 2100. We project about a 3% increase in cropland and an 8% increase in pasture by 2050. Cropland then decreases through 2100, to about 2% less than in 2015. We also see a slight decline in pasture by 2100 compared with 2050, so that it is only 3% above the 2015 level. Despite an expansion of biomass energy of about 250% by 2050 from 2015 levels, land used by biomass production accounts for less than 1% of the land in crops in 2050. The expansion of crop, pasture and bioenergy land comes mostly from natural grassland areas—the area in grassland in 2050 is only 86% of that in 2015, but after 2050 there is a slow but steady increase. The area in managed forest increases by about 4% by 2050, and nearly 14% by 2100.

The picture varies somewhat when we look at our major regional groups (**Figure 17**). We see very little deforestation in the *Other G20* and *Developed* region, but somewhat more in the *Rest of the World*. There natural forest areas decline by about 7% by 2050 and 8% by 2100 from 2015. We see fairly significant expansion of cropland in the *Developed* and *Rest of the World* regions from 2015 (15 and 17%, respectively by 2050, and 13 and 12% by 2100). In both regions most of the increases in managed land (crops, pasture and managed forest) comes from natural grassland, with some loss of natural forest.

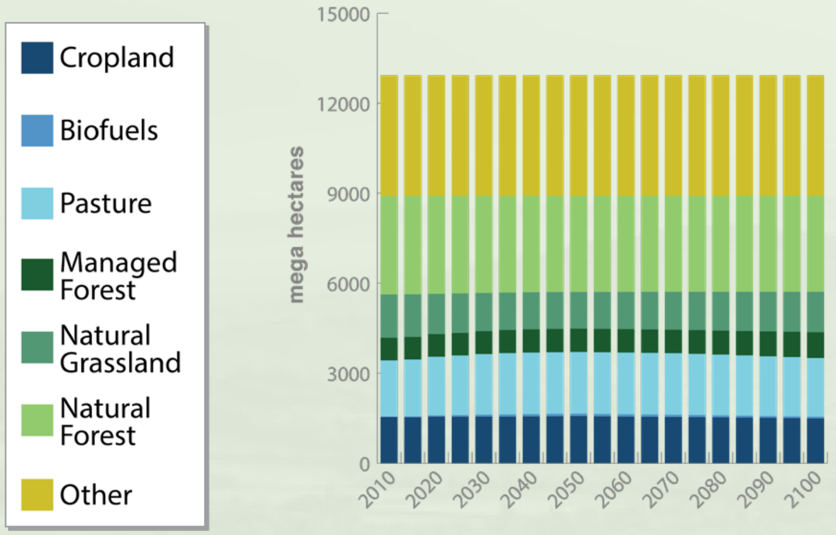

Figure 16. Global land use (Mha)

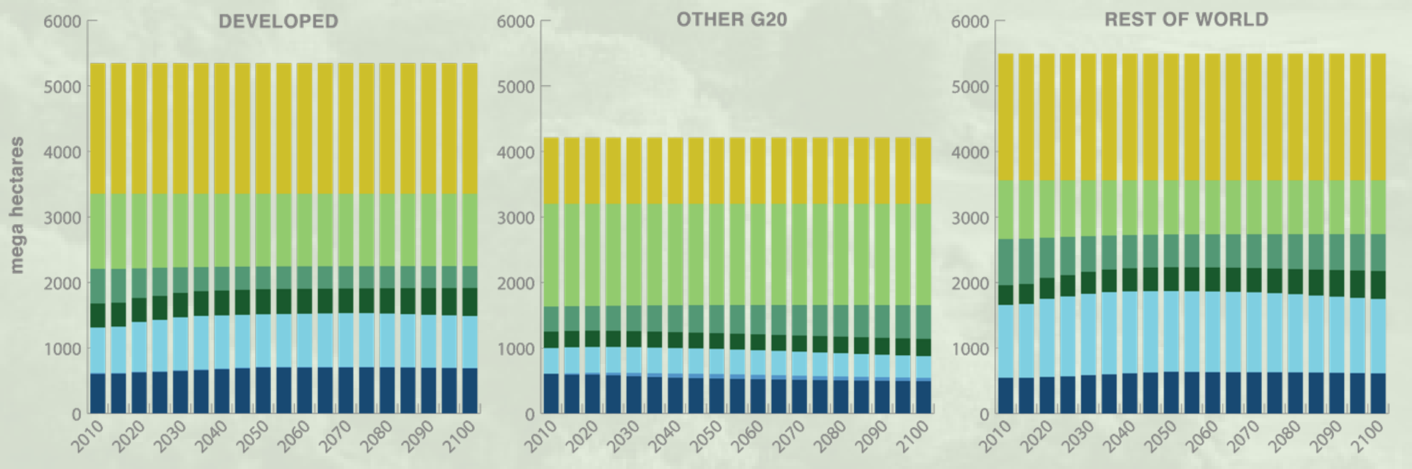

Figure 17. Land use by major group. *Developed* (left), *Other G20* (center), and *Rest of the World* (right)

Energy Prices

The EPPA model represents both demand and supply factors for all goods, including energy and agricultural commodities. It resolves demand and supply by finding prices that clear markets.[4] As such, prices are an output of an EPPA simulation rather than an input assumption. As EPPA is structured, energy and agricultural commodities rely on natural resources whose supply is limited. Agricultural commodities rely heavily on land, a renewable resource that provides an annual flow of productive capacity. Gradually increasing demand results in higher land prices and thus higher commodity prices. This can be offset by conversion of unmanaged land to crop and pasture land, and by an increase in land productivity. Fossil energy resources are characterized as depletable resources—as more are used over time, further development of potentially more expensive resources is needed, again tending to raise the cost of fossil energy commodities in forward simulations. Energy-efficiency improvements, policies aimed at reducing fossil energy use, and technical change in energy-producing sectors can have offsetting effects.

Prices of energy and agricultural commodities are highly variable from year to year, and are subject to periodic large swings, sometimes rising three or four-fold in the matter of a year or so, and then collapsing back to earlier levels. This variability leads many analysts to conclude that it is folly to try to project prices. With EPPA we have not attempted to represent processes that give rise to short-term commodity price dynamics, which include swings in expectations, depletion or accumulation of stocks, short-run disruptions to supply, and political factors. We report the price indices here, not so much to offer an accurate projection but rather to help understand how prices are affecting choices among energy commodities, land use and other projections.

Between 2015 and 2050, we see very little increase in fuel prices in our projection, despite their characterization as depletable resources (**Figure 18**). Oil and gas prices rise by generally less than 10%. Coal prices fall by about 9%. Here we report global average prices. Oil is approximated as a homogeneous commodity with a single world price (in reality there are different grades of oil with somewhat different prices). Gas and coal are modeled as regional commodities, and so prices can vary from one region to another but will tend to be tied together because of competition from foreign trade. Prices for these commodities combine pure resource rents and the cost of producing a marketable product from the resource. While depletion increases the pure rent in the model, all other things being equal, the existence of sunk capital and a continuing flow of production in the face of weakening demand will mean that the price can fall below the full cost of production. Energy-efficiency improvements and policies directed against using fossil resources, especially coal, where the pure resource rent is small, lead to an actual decrease (coal) or very small increases (gas, oil) in prices.

Given declining or stable fossil fuel prices, and their importance in electricity production, it is perhaps surprising to see electricity prices rising. One explanation is the policy requirement in many regions to include more low-carbon generation options. Also, in many developed countries, this requirement is coupled with overcapacity of old generation plants that are now producing at prices that would not recover the full cost of replacing these plants given current environmental policies. As long as this old capacity is available, it can fill in for intermittent renewables. However, as the old capacity depreciates, higher prices are needed to encourage new capacity. Overall, the global average electricity price rises gradually to about 31% above 2015 levels by 2050.

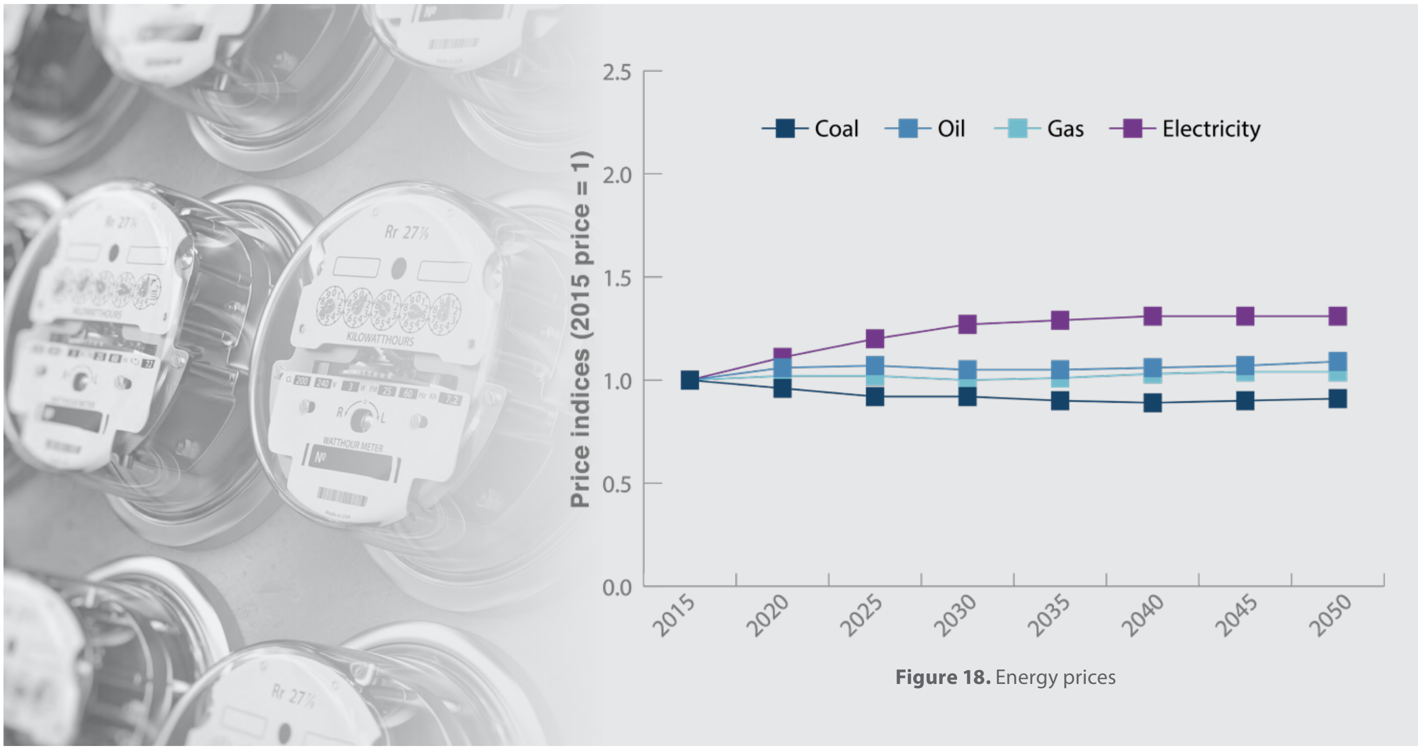

Figure 18. Energy prices

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[4] Within the general equilibrium framework, prices are relative to one another, and so one must choose a "numeraire" good whose price is by definition 1.0. Within EPPA we choose the price of aggregate consumption in the USA as the numeraire good. Price indices for other goods (aggregate consumption in other regions, commodities and factors of production) are hence reported relative to the price of aggregate consumption in the USA. A broad good as the numeraire, the price of consumption, means it is approximately consistent with reporting GDP and consumption in real terms—so that increases represent a real increase in the amount of goods and services available in the economy—and that product prices that deviate from 1 indicate increases or decreases in the cost of those goods relative to the overall price level in the economy.

Emissions and Climate

GHG Emissions by Gas/Source and Region

Anthropogenic GHG emissions result from a wide range of industrial, agricultural and consumption activities. Combustion of fossil fuels is by far the largest source of carbon dioxide (CO_2), and the largest source of anthropogenic GHG emissions. Methane (CH_4), converted to CO_2-e using Global Warming Potential (GWP) indices, is the second largest, but it has many sources, including those related to fossil energy production and distribution, agricultural activities and waste management. The largest anthropogenic sources of methane are livestock and rice production. Nitrous oxide (N_2O) from both combustion and agricultural soils, but mostly related to nitrogen fertilizer, is the third largest source of anthropogenic GHG. Industrial sources of CO_2, mainly from cement production, fluorocarbons (PFCs, HFCs, SF_6) and land-use change, are smaller anthropogenic sources of GHGs. Emissions related to land-use change are subject to different definitions (net or gross, and what constitutes anthropogenic—see **Box 5**). Our modeling of anthropogenic land-use CO_2 emissions is a net emissions concept: Deforestation and resulting emissions from combustion of biomass or decomposition is a source, but this is partly offset by uptake from regrowing forests or management practices on cropland that can lead to carbon uptake.

Our accounting of emissions here includes those gases directly discussed as subject to control under international climate agreements. Chlorofluorocarbons (CFCs) remain a major source of radiative forcing, but their emissions have largely been phased out under the Montreal Protocol because of their ozone-depleting properties. Tropopospheric ozone contributes to ra-

Box 5.

The Contribution of Land to Changing CO_2 Concentrations

There are a variety of estimates of GHG emissions related to land systems and land-use change, and multiple methods for estimating them. One distinction among such methods is the contribution of anthropogenic activity and its effect on sources and sinks of GHG emissions from land compared with the total effect of land systems. Other distinctions include the gross or net effects of deforestation, or of all anthropogenic activities on land use in general. Some estimates attempt to come up with the contribution of deforestation. Others attribute emissions to different land-use types and to biomass burning, and hence emissions from deforestation will show up in different categories of land use, depending on what happens to the land after it is deforested.

The IPCC has concluded that top-down approaches that attempt to balance the carbon cycle find that land systems as a whole are a net sink for carbon, while bottom-up approaches that attempt to attribute changes to anthropogenic activities show land systems as a net source (Smith *et al.* 2014). These are not necessarily contradictory, but if human activities are a net source, then other "natural" changes must be a net sink for these estimates to be consistent. The World Meteorological Organization (WMO) provides a carbon budget for accounting year 2015 (**Table 2**), showing a mean estimate of land-use emissions of 1.3 Gt C (4.8 Gt CO_2) and a mean land sink of 2 Gt C (7.3 Gt CO_2), implying that the land system as a whole is a net sink of 0.7 Gt C (2.6 Gt CO_2) with significant error bars on these estimates.

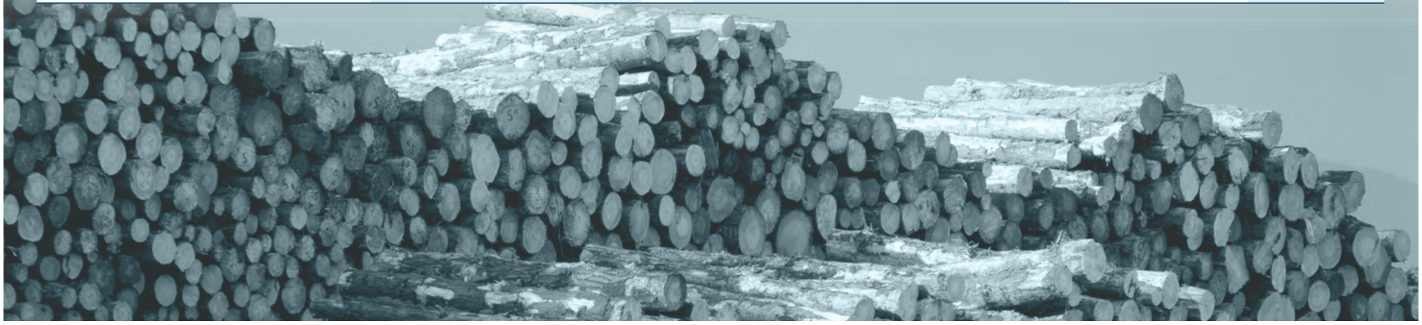
Methods for estimating anthropogenic emissions include: (1) bookkeeping methods that track land-use change, and use carbon coefficients and growth-response functions to estimate changes in net fluxes due to deforestation; (2) models that simulate emissions and stock changes implied by land-use change; and (3) satellite data on changes in forest cover combined with estimates of changes in carbon stocks associated with forest-cover changes.

The IPCC Fifth Assessment Report (AR5), an authoritative review of the literature (Smith *et al.*, 2014), reported data extending only through 2007. More recent trends are highlighted by Houghton and Nassikas (2017) and the Food and Agriculture Organization (FAO, 2015) with estimates through 2015. The FAO estimated that emissions from deforestation and forest degradation dropped from an average of 3.9 Gt CO_2 for the period 2001–2010 to 2.9 Gt on average for the period 2011–2015, and that there was a forest sink of 2.1 Gt resulting in a net source of just 0.8 Gt CO_2. Houghton and Nassikas provide estimates from 1850 to 2015, noting that emissions were "generally increasing over time to a maximum of 2.10 Pg C yr^{-1} in 1997" (7.7 Gt CO_2). According to Houghton and Nassikas, "for the most recent decade (2006–2015) global net emissions from LULCC averaged 1.11 (±0.35) Pg C yr^{-1}, consisting of a net source from the tropics (1.41 ± 0.17 Pg C yr^{-1}), a net sink in northern midlatitudes (0.28 ± 0.21 Pg C yr^{-1}), and carbon neutrality in southern midlatitudes" (for global net emissions of 4.1 Gt CO_2). For the comparable 2011–2015 period, the Houghton and Nassikas average is 3.9 Gt CO_2. The FAO and Houghton & Nassikas estimates differ by a substantial amount, but both require additional uptake of carbon by land in order to balance the total carbon budget estimated by the WMO when median estimates of other sources and sinks are considered.

Given our modeling approach in EPPA, land-use emissions reported in **Figure 19** are only an accounting of emissions from forests transitioning to other land uses. It does not factor in emissions or sinks related to other land transitions, forest degradation, or legacy emissions or sinks from historical land-use change. These other sources and sinks are accounted for in an adjustment within the IGSM so that our carbon cycle is consistent with observed changes in the atmospheric concentrations, given our modeling of the ocean, terrestrial systems and emissions from fossil fuel and cement production.

Table 2. Annual Global Carbon Budget (units of gigatons of carbon per year, GtC yr-1) (Source: Candela and Carlson, 2017)

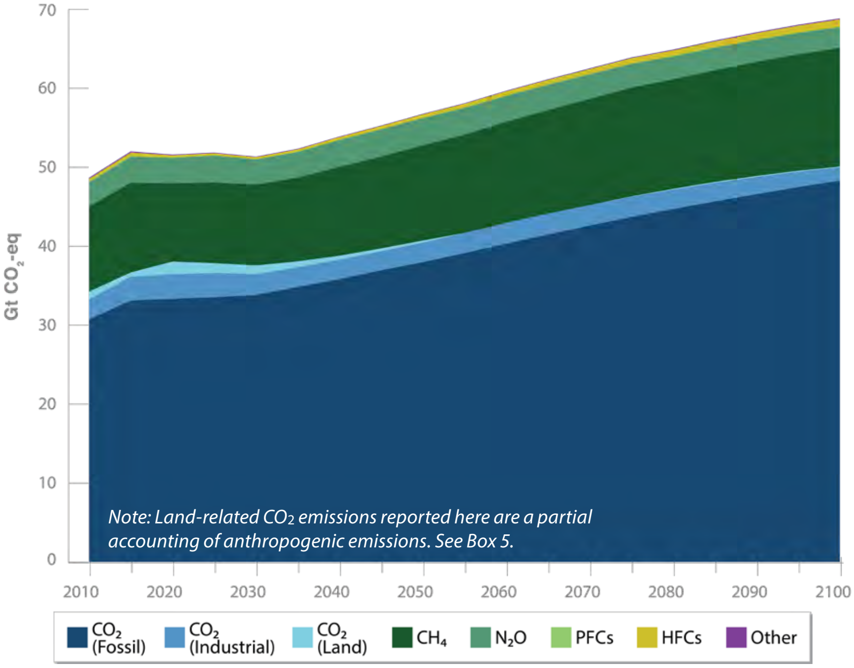
9.9 ± 0–5	1.3 ± 0.5	=	6.2 ± 0.2	3.0 ± 0.5	2.0 ± 0.9
Fossil fuel emissions (includes cement production)	Land use change, primarily deforestation		Growth in atmospheric concentration (6.2 GtC = 2.9 ppm)	Uptake by the ocean	Uptake by land



diative forcing, and aerosols variously have warming or cooling properties. Anthropogenic emissions contribute indirectly to the formation of ozone and aerosols in the atmosphere. These are accounted for in our model and contribute to our simulation of future climate change; we also simulate future anthropogenic emissions of precursor substances. However, there is no simple way to convert those precursor emissions to a CO_2-e basis, and so they are not included in Figure 19 or Figure 20.

Our projections show emissions of the major greenhouse gases increasing from 52 gigatons (Gt) CO_2-e in 2015 to just under 69 Gt by 2100 under our representation of current NDC commitments, extended through the century (**Figure 19**). Total emissions are fairly flat through 2030, and they gradually increase after that. The relative importance of different gases and sources remains about the same over time. Methane's share of emissions remains at about 22%. Emissions from deforestation are projected to gradually disappear as the pressure to convert forest to crop and pasture land becomes negligible.

As described earlier, our evaluation of the NDCs assumes that they are met, and covers more countries than in previous Outlooks. Previous projections were limited to major emitting countries/regions and assessed likely reductions, sometimes falling short of NDC commitments. Other factors such as GDP growth, renewables deployment, population growth and the cost of various energy alternatives have also changed from earlier Outlooks. The combined effect of these changes is generally lower total emissions over the century than in previous Outlooks. Global emissions in our current projection are about 4% lower in 2025 than in our 2016 and 2015 Outlooks, about 8% lower in 2030, and about 11% lower in 2050. Our regional evaluation of progress toward meeting the Paris NDCs (discussed in **Prospects for Meeting Short-Term Paris Commitments,** p. 32) suggests that some countries are on track to meet or exceed their initial targets, while others would need additional policies to meet their goals. To understand the ultimate effect of measures delineated in the Paris NDCs will require ongoing updates of progress. Of course these NDCs only specify targets through 2030, and so whether or how such measures would be extended or deepened beyond 2030 is speculative.



Note: Land-related CO_2 emissions reported here are a partial accounting of anthropogenic emissions. See Box 5.

Figure 19. Global annual greenhouse gas emissions

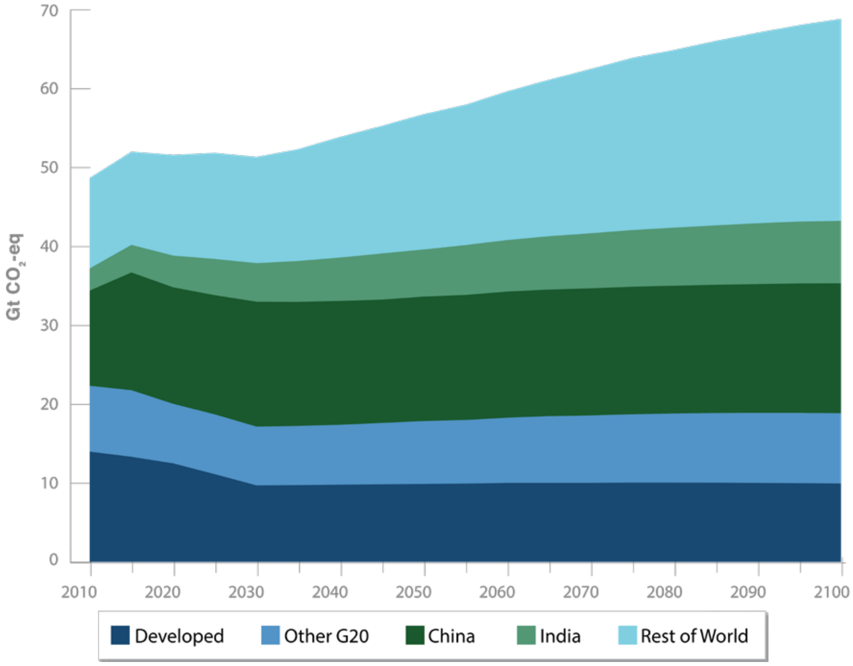


Figure 20. GHG annual emissions by major group

Overall, projected emissions by major country groups (**Figure 20**) show trends similar to those reported in our previous Outlooks. The NDCs of countries in the *Developed* region generally have absolute reductions in emissions, and so emissions fall through 2030. And by our assumption of simply extending these commitments without further reductions, emissions remain flat after that. The *Other G20*, excluding China and India, succeed in reducing emissions somewhat through 2030, but without absolute emissions reductions in all of these countries, emissions drift back up over the rest of the century. China also manages to peak emissions, and then in our projections these are basically flat, only slightly increasing. Again, we have not implemented specific new measures beyond 2030, and so China's intensity target eventually becomes non-binding. The more significant increases in emissions come from India and the *Rest of the World*. The combination of absolute decreases among the *Developed* countries in early years, and then gradually increasing emissions from India and the *Rest of the World*, give rise to an intially flat trend in global emissions that eventually rises.

Box 6.

Current Greenhouse Gas Concentrations

Ray Wang, Georgia Institute of Technology • Ronald Prinn, MIT

Plotted in **Figure 21** are concentrations of CO_2, CO_2-eq (Kyoto) and CO_2-eq (IPCC) including the annual seasonal cycle and smoothed trend over time, following the approach described in Huang *et al.* (2009). The non-CO_2 gas concentrations are measured in the AGAGE network (Prinn *et al.*, 2018) and the CO_2 concentrations are from NOAA Global Monitoring Division (NOAA, 2018).

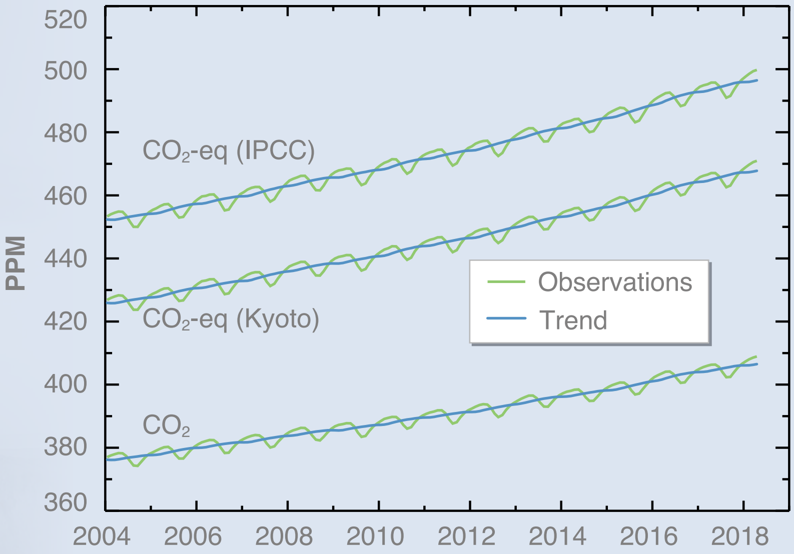


Figure 21. Current GHG concentrations

Implications of Recent Emissions Trends and Future Projections

While aggregate growth in GHG emissions has slowed in recent years, especially in 2015 and 2016, concentrations have continued to rise inexorably (**Box 6**). This difference, between varying growth in emissions and a stable, near-linear rise in concentrations, stems from the fact that most greenhouse gases are very long-lived in the atmosphere so that a roughly constant emissions level means essentially constant linear growth in concentrations. For concentration growth to slow, emissions would need to drop substantially. This underscores the challenge of stabilizing GHG concentrations and ultimately halting the rise in temperature. To do so requires that emissions eventually drop to zero, with most estimates suggesting the need for a decline on the order of 80% from current levels by 2050, and then a further decline in order to stay below a 2°C rise in temperature. Greenhouse gases also have different lifetimes and radiative effects while in the atmosphere, complicating comparisons of total GHG emissions and their contributions to GHG concentrations in a CO_2-equivalent metric. Methane has a relatively short lifetime, and moderate cuts in its emissions would lead to declining methane concentrations. Common CFCs have lifetimes ranging from 55 to 140 years (Elkins, 1999), and so even though their emissions have been virtually eliminated, there is essentially no decline in concentrations over the 14-year period depicted.

In 2015 and 2016, the growth in total GHGs, and especially that of CO_2, was the slowest since the early 1990s, except for the global recession years of 2007–2009, and has been attributed mainly to switches from coal to gas and increased renewables in the power sector (Olivier *et al.*, 2017). Olivier *et al.* (2017) also notes revisions from previous reports due to updates in fuel-use estimates, changes in some emissions coefficients, and generally greater uncertainty in estimates of emissions of CO_2 from land-use change and non-CO_2 GHGs, with the latter continuing to grow at about 1% per year.

Emissions trends resulted in continued increases in concentrations of CO_2 and of total greenhouse gases. CO_2 concentrations vary over the year because of the annual uptake of CO_2 by land vegetation in the spring, and release in the fall, with a larger seasonal contribution from the northern hemisphere due to its greater landmass. Removing this annual variation, the trend line continues to rise at a near-linear rate, adding just over 2 ppm per year each year, and exceeding 405 ppm as of April 2018. We show in Box 6 the total concentrations of those GHGs identified for control under the Kyoto protocol, which are labeled CO_2-eq (Kyoto) and are the focus of most needed additional emissions reductions, and the total including CFCs labeled CO_2-eq (IPCC). Emissions of CFCs have been largely phased out under the Montreal Protocol because of their stratospheric ozone-depleting properties. Emissions of other gases (CH_4, N_2O, HFCs) continue to increase, widening their contribution to radiative forcing somewhat over time. Total GHG concentrations, including all the long-lived non-CO_2 GHGs, is now approaching 500 ppm CO_2-eq. The total radiative forcing from all GHGs is partly offset by the cooling effect of sulfate aerosols, which is uncertain, but whose direct and indirect effects are estimated to coincidentally offset the warming contribution of non-CO_2 GHGs (Myhre *et al.*, 2013). Hence the net radiative effect is coincidentally around that of CO_2 alone, about 400 ppm CO_2-eq.

It is generally estimated that concentrations of 450 ppm CO_2-eq are approximately consistent with an equilibrium 2°C rise in temperature with mid-range estimates of Earth-system responses to radiative forcing. We have as yet seen only a little more than 1°C of warming, in part because of the cooling effect of aerosols, and in part be-

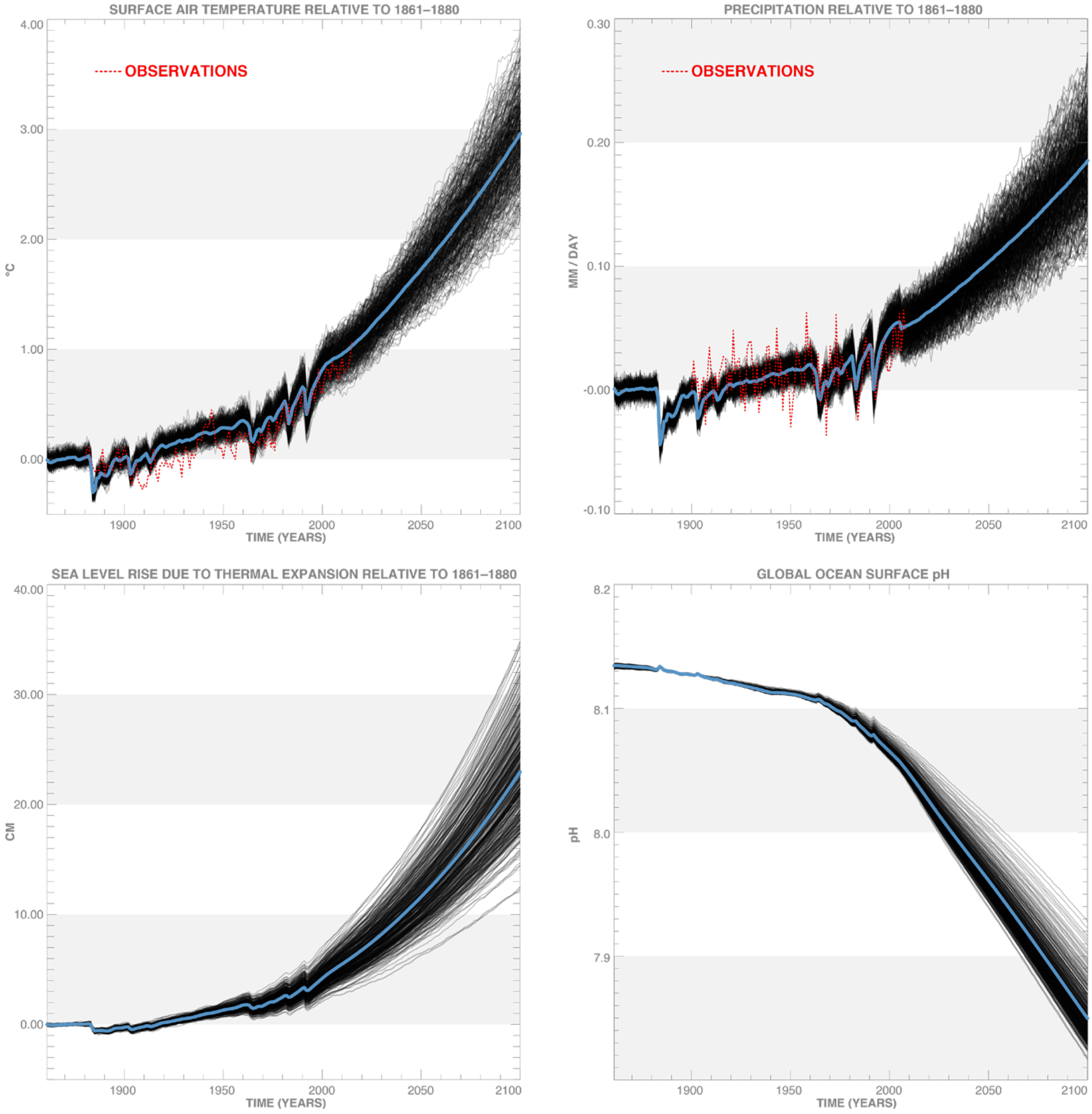


Figure 22. Values projected in a 400-member ensemble run of the IGSM. **Top:** (left) Surface air temperature (°C) and (right) precipitation (mm/day) relative to the mean values in the period 1861–1880. **Bottom:** (left) sea-level rise (cm) due to thermal expansion relative to the mean values in the period 1861–1880; (right) global ocean surface pH from 1861 through 2100.

cause it will take many decades to approach the equilibrium temperature consistent with today's concentrations. The role of aerosols and inertia in the climate system highlight yet additional challenges for stabilizing temperatures. First, we are committed to a considerable rise in temperature even if further concentration increases are halted. Second, if we eliminate aerosol emissions as we would do if we greatly reduced CO_2 emissions—because the aerosols are largely due to coal combustion—it will unmask the full effect of long-lived GHGs.

Our simulation of global temperature, precipitation, sea-level rise and ocean pH (**Figure 22**), and of CO_2 concentrations (**Figure 23**) utilizes a new version of our IGSM framework and new estimates of uncertainty in the climate-system response (Sokolov *et al.*, 2018). With increasing computational power, we are now able to simulate large ensembles of our efficient MESM model. As a result, we show a full distribution of a 400-member ensemble run, using Latin Hypercube sampling from the joint probability density function for climate sensitivity, ocean heat uptake and aerosol response.[5] The median increase in global mean surface air temperature by 2100, above the mean value in the period 1861-1880, is 3.0°C—the 10 and 90% confidence limits of the distribution are 2.6 and 3.5°C, rounding to the nearest 0.1°C. The projections show median global precipitation to increase by 0.18 mm/day above the 1861-1880 level by 2100, with a 10 and 90% range of 0.15 and 0.22 mm/day. Projected median sea-level rise above the 1861-1880 level is 0.23 m in 2100, with a 10 and 90% range of 0.18 and 0.28 m. The sea-level rise estimates include only that due to thermal expansion. By 2100, the median ocean pH falls to 7.85 from a preindustrial level of 8.14 in 1861, with a 10 and 90% range of 7.83 and 7.88.

Sea-level rise will likely be somewhat greater due to contributions from glaciers and ice sheets. Our IGSM does not have a component that estimates the potential contribution from the melting of ice sheets (i.e. Greenland, Antarctic). The evidence is that this ice is melting and adding to sea-level rise. Significant melting could add meters of sea-level rise, however, most likely over several centuries. The IPCC expressed "medium confidence" that during this century the additional contribution from large ice sheets would not exceed several tenths of a meter (Church *et al.*, 2013). This continues to be an active area of research; scientists are investigating various mechanisms that could be involved and may be accelerating melting. Regardless, there is enormous inertia in thermal expansion and ice-sheet melting; even if other aspects of the climate stabilized in this century, sea-level rise would continue for centuries, adding up to potentially meters of rise unless GHG concentrations are stabilized at 500 ppm or below.

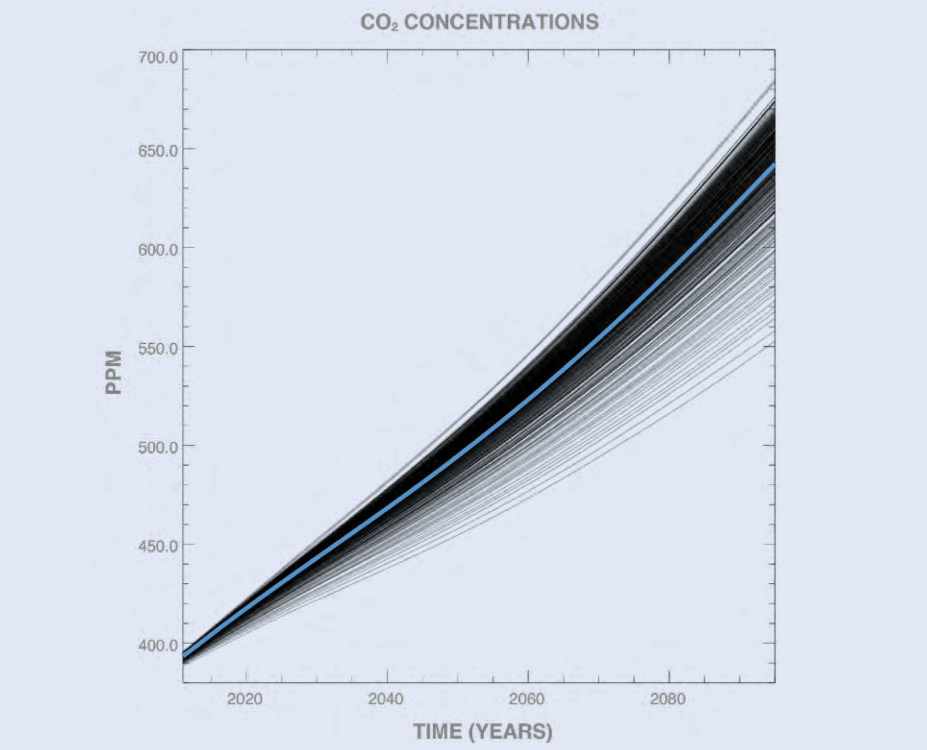


Figure 23. CO_2 concentrations in a 400-member ensemble run of the IGSM.

Median values for continental (North America, Europe, Asia, Australia, Africa, South America) temperature increases vary from slightly below to slightly above 4°C by 2100 (**Figure 24**). We calculate these values using a downscaling approach (Schlosser *et al.*, 2012), using the 400-member ensemble of our 2-D IGSM and 34 GCM longitudinal patterns. In general, these show more warming than the global average because warming is generally greater over land than over the ocean. The continental results also reflect the general result that warming is greater at the poles than at the equator. These large continental regions cover a broad range of latitudes, and so this greater poleward warming is not dramatically evident. However, the areas centered on the equator (South America, Africa, Australia) show less warming.

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[5] As noted earlier, although the EPPA model has many uncertain parameters, these are not varied (e.g., Webster *et al.*, 2012). Uncertainty in underlying EPPA parameters in regions without absolute emissions caps would contribute to emissions uncertainty. In regions with absolute emissions caps, uncertainty in EPPA parameters would mostly contribute to uncertainty in costs, because emissions are prescribed. We also do not represent uncertainty in policy implementation to meet emissions goals.

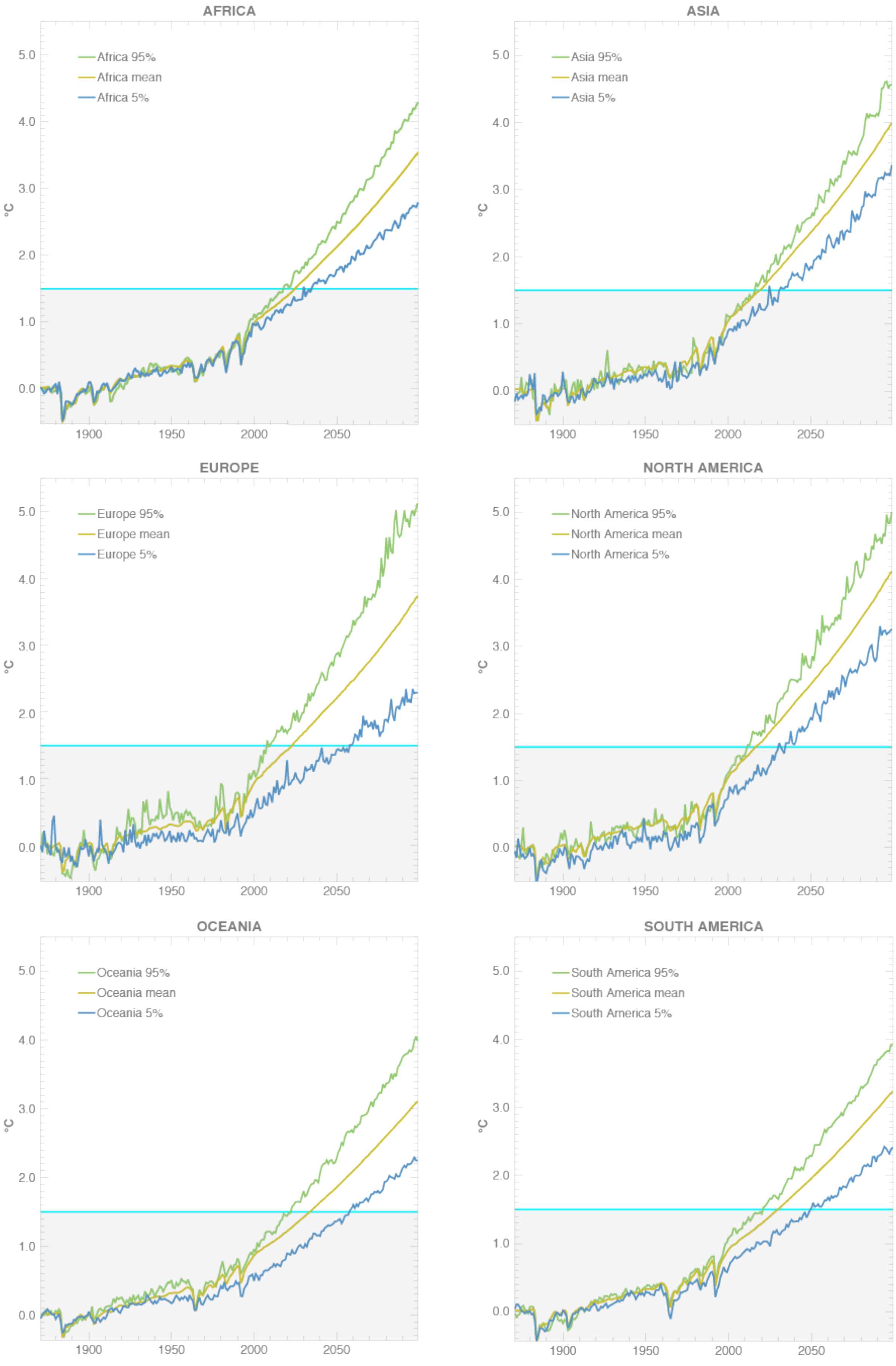

Figure 24. Annual mean surface air temperature for different regions relative to the 1861–1880 mean

Water and Agriculture

The world's water and food systems depend heavily on the use of natural resources. Agriculture is a large user of water and consumes energy directly and indirectly through energy-intensive inputs such as nitrogen fertilizer. This sector contributes to greenhouse gas emissions, is a major source of nitrous oxide and methane emissions, and its use of energy and land contributes to carbon dioxide emissions. Water and food systems are also directly affected by climate.

In this section we include a risk analysis, focusing on water stress in the U.S. that results from our combined climate and economic projections. We report results from our central economic/emissions projection for agriculture including levels of food, crop and livestock consumption and global commodity prices. We also include speculative simulations on the potential impacts of climate change on agriculture. These speculative simulations are not based on the climate simulations presented in this Outlook but are an attempt to summarize the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) review of impacts on agricultural yields to illustrate how that degree of yield change would affect global agriculture markets (IPCC, 2014).

Finally, we include two broader perspectives—one on the future of water resources, and the other on major transformations that are now underway in agriculture.

Water Resources: Changing Nature of Risks

We have assessed the trends in managed water stress simulated by the Water Resource System (WRS – Strzepek *et al.*, 2013) within the IGSM. The WRS is forced by the global simulations of climate from the MESM 2018 Outlook scenario with spatial downscaling (Schlosser *et al.*, 2012) updated with the most recent Coupled Model Intercomparison Project Phase 5 (CMIP5) regional climate information. In addition, the socio-economic drivers from the MIT EPPA model Outlook scenario are used to drive the water-demand sectors. At each Assessment Sub Region (ASR) of the WRS, we calculate a Water Stress Index (WSI) as the ratio of total water withdrawals to the total surface water supply (sum of the basin's runoff and inflow from upstream basins). The changes in WSI are assessed with respect to the WRS forced by observed historical climate conditions (**Figure 26**).

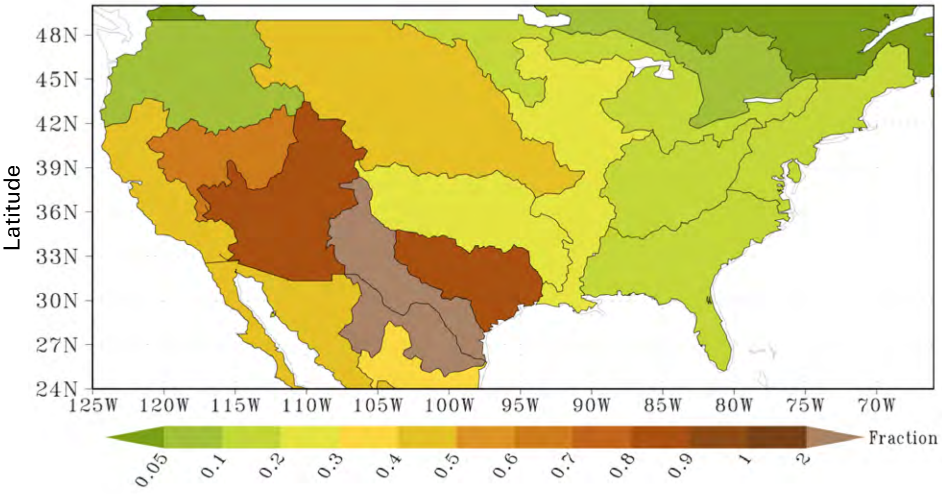

Figure 26. Contemporary Water Stress Index (WSI, unitless) estimate over the contiguous U.S. Based on an average for the years 2001–2010 from the Water Resource System (IGSM-WRS) simulation.

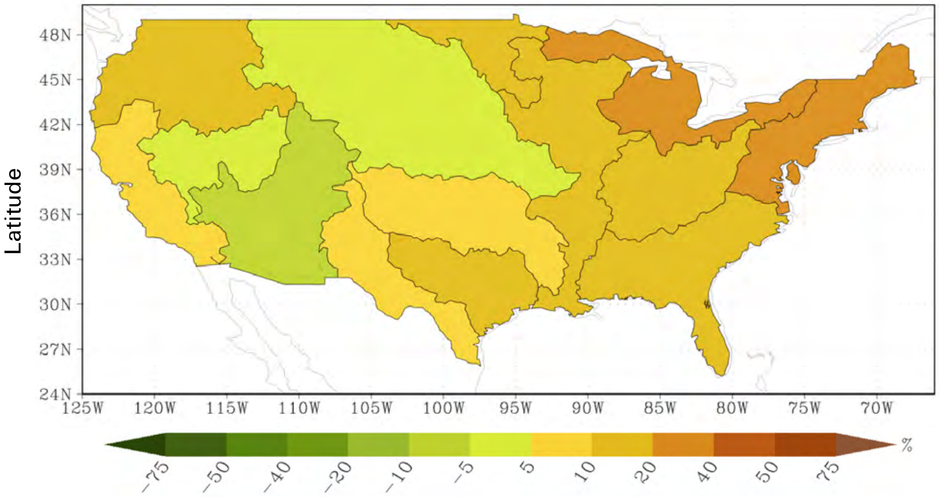

Figure 27. Relative changes (%) in the 2041–2050 averaged WSI simulated by the IGSM-WRS and driven by the climate and socio-economic projections of the 2018 Outlook scenario. Changes are relative to the 2001–2010 averaged WSI results.

Maps are based on the large ensemble of simulations (based on a hybrid combination of over 7,000 possible regional climate outcomes with the 400-member ensemble of the IGSM) performed by the WRS. Results show the median value of change for each ASR, and thus the "central tendency" (half the ensemble with higher values and the other half lower values) of projected water-stress changes.

In this report, we focus on an important advance in our assessment capabilities. The WRS framework now incorporates the entire climate and socio-economic spectrum of our IGSM uncertainty framework to provide a more comprehensive risk-based assessment of future water resources. In addition, this analysis can be targeted across any region of interest. In recent work we have focused on the changing character of water-stress risks over southern and eastern Asia (Fant *et al.*, 2016 and Gao *et al.*, 2018). Below we present results from our Outlook scenario and highlight the risk to water-stress changes over the coming decades (by midcentury) over the contiguous United States.

In the context of this analysis, it is important to recognize that our WRS framework presents an assessment of stress pertaining to "sustainable surface water," in that the model only allocates groundwater at the rate of natural recharge. Therefore, we do not make any explicit assessment of unsustainable groundwater pumping and its severity/risk relative to the finite aquifer supplies of water (although we intend to pursue this in future analyses). In addition, the configured spatial coarseness of the ASRs prevents this analysis from identifying practical risk-reduction strategies and solutions at a local/community scale. Nevertheless, our framework provides a "triage-level risk assessment," which can then be used to guide and prioritize higher-resolution configurations of the ASRs needed for such targeted studies.

Similar to numerous assessments of water scarcity, stress, availability and other metrics that have been conducted by the scientific community, our contemporary landscape of water stress over the contiguous U.S. displays the abrupt transition of low to high water stress between ASRs east and west of the Mississippi River (Figure 26). The northwest U.S. benefits from low water stress primarily supported through ample precipitation (and subsequent runoff) that it receives throughout the year. Conversely, the south and southwest regions experience considerable water-stressed conditions.

Relative to the current landscape of water stress, we find that for the large ensemble of simulations that have been conducted with our probabilistic framework of our Outlook scenario, the "central tendency" of water-stress changes (equal likelihood of increased and decreased changes) is to place relatively higher increases of stress over basins that currently experience low stress (**Figure 27**). The largest *relative* increases in WSI are seen over the northeast U.S. and are primarily the result of increases in the non-agricultural water-demand sectors, and thus driven by increases in population and economic activity. This underscores the finding of Schlosser *et al.* (2014) that adaptive measures will be needed to meet additional surface-water shortfalls—even under aggressive climate mitigation pathways. Looking further into the details of the large number of simulations we have conducted for this assessment, we find details that convey salient risks in a number of basins.

Overall, the results highlight the impact of the regional details of climate change and how we are able to convey risks to water resources by midcentury. The most notable feature is the asymmetric behavior in the sign and corresponding strength of water-stress changes, as a result of the regional patterns of climate change associated with the global climate sensitivity response—both of which the MESM module accounts for in the IGSM simulations. Comparing the left and right panels of **Figure 28** and **Figure 29**, we find that over most of the southern, southwestern and western basins of the U.S., water stress is more likely to increase than decrease. In some basins, particularly over the eastern portion of the U.S., there is no outcome across the distribution of simulations that results in a decrease in water stress. As previously noted, this feature is largely a result of the growth in population and economic activity that subsequently increases non-agricultural water-sector demands.

An additional feature seen particularly over the northeast U.S. basin is that the range of possible outcomes in WSI change is small (yet in all cases positive) and primarily confined to within a 20–40% increase in water stress by midcentury. This stronger consensus (compared to other basins) across the large number of simulations indicates that—even when considering all the uncertainties included within our climate and socio-economic projections—there is higher confidence in the sign and severity of water-stress change by midcentury for this region.

Conversely, for most of the basins across the southwestern U.S., the risk of water-stress changes spans a larger range of possible outcomes. Our assessment indicates that while there is a 1-in-10 chance of these basins experiencing at least a 40% increase (and in some basins over a 75% increase)

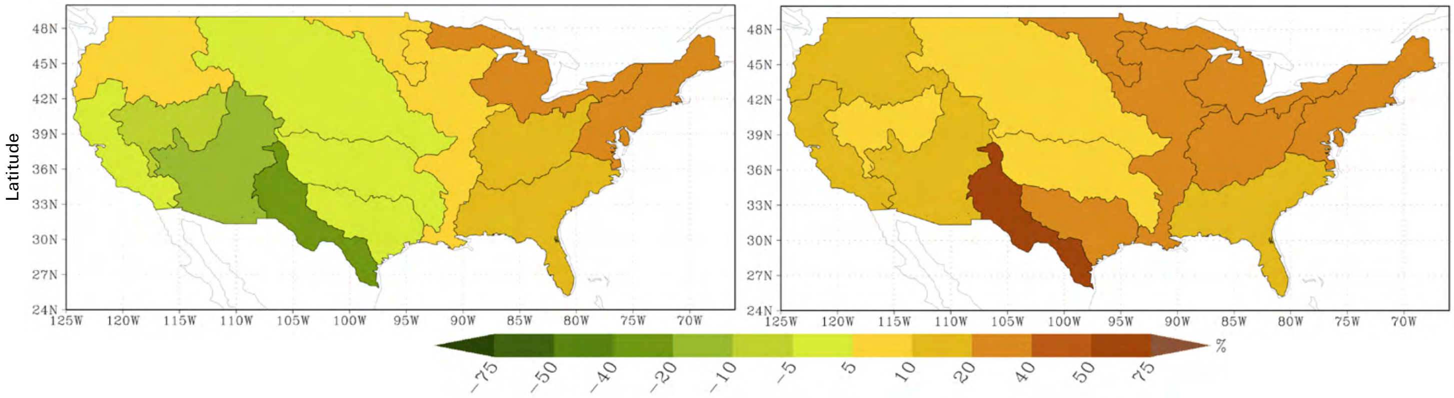

Figure 28. The inter-quartile range of relative changes (%) to the 2041–2050 averaged WSI simulated by the IGSM-WRS, driven by the climate and socio-economic projections of the 2018 Outlook scenario. Changes are relative to the 2001–2010 average. The maps show for each ASR the lowest 25% (left panel) and highest 75% (right panel) value of WSI change across the entire ensemble.

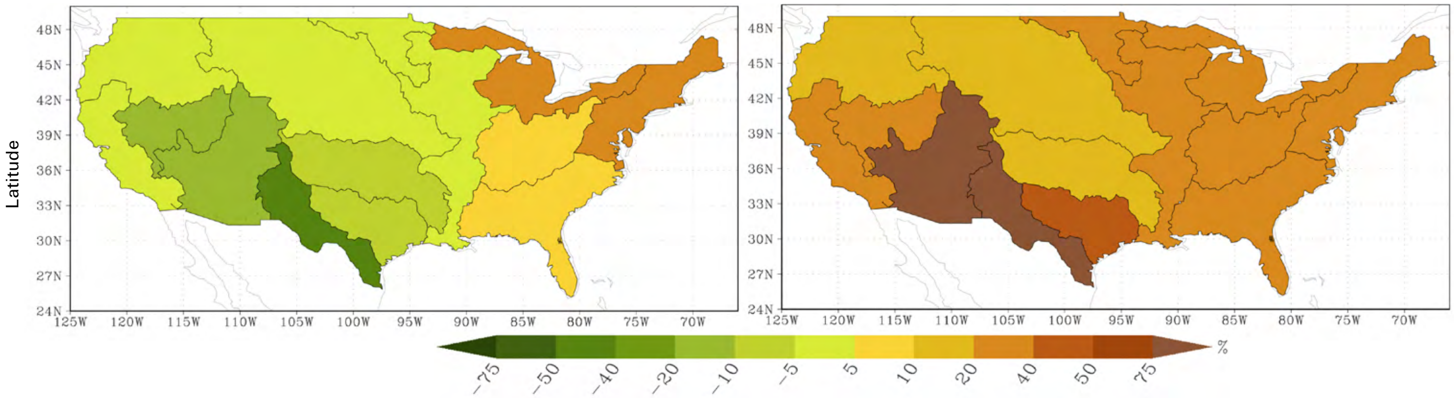

Figure 29. The 10th (left panel) and 90th (right panel) percentile range of relative changes (%) to the 2041–2050 averaged WSI simulated by the IGSM-WRS, driven by the climate and socio-economic projections of the 2018 Outlook scenario. Changes are relative to the 2001–2010 average.

in water stress, there is an equal likelihood (1-in-10 chance) of the same basins experiencing a decrease in water stress of upwards of 20% (and up to 50% for the Rio Grande). Closer to the extremes of this risk characterization, we find an even more egregious asymmetry to the high- and low-end values of water-stress changes, and this skewness is weighted more toward increased water stress (**Figure 30**). For example, for the upper Mississippi Basin, while there is a 1-in-20 chance that water stress could decrease by as much as 10%, there is an equal likelihood that the basin will experience water-stress increases of at least 40–50%. The majority (or entirety) of this range is attributable to the uncertainty in the regional climate patterns that emerge from the human-forced climate response. However, there is a very notable impact and risk of heightened water stress caused by population and economic growth.

Overall, these results underscore the merits of applying a multi-sector, risk-based modeling framework to the assessment of the growing threats to U.S. water resources in a changing world. Even when considering a world with international commitments to reduce emissions so as to avert climate change, there are numerous regional intricacies to changes in climate, natural and managed ecosystems, population and economic activity. By considering all the plausible pathways that ultimately satisfy the same global objective (avoided climate warming), we have shown that the changing nature of water stress over the U.S. carries both gains and losses—but with very unequal likelihoods. The outlook is that by midcentury there is a greater likelihood of widespread, substantial increases in water stress, and that adaptive measures will be required to overturn this imbalance of risk.

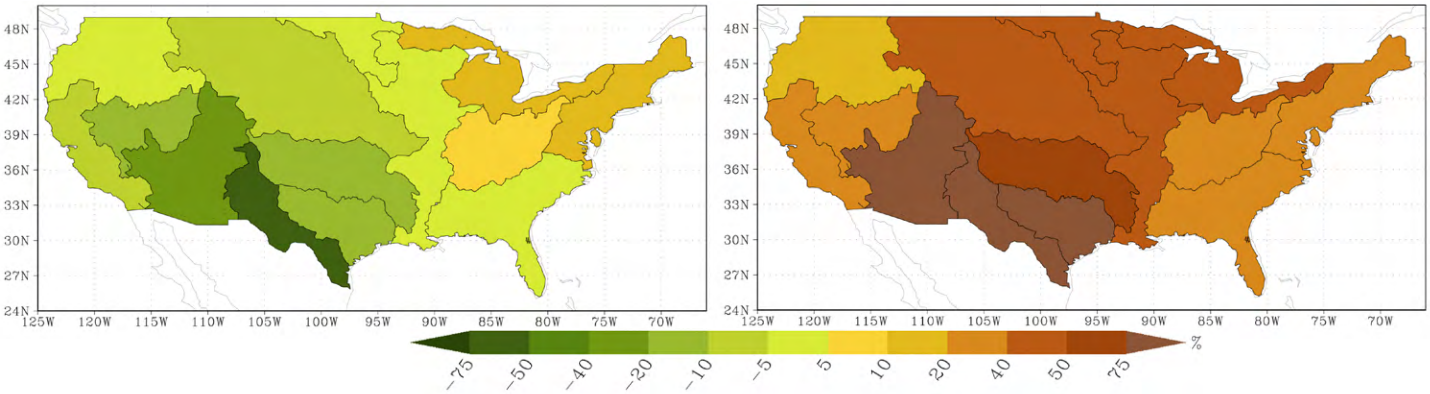

Figure 30. The 5th (left panel) and 95th (right panel) percentile range of relative changes (%) to the 2041–2050 averaged WSI simulated by the IGSM-WRS, driven by the climate and socio-economic projections of the 2018 Outlook scenario. Changes are relative to the 2001–2010 average.

Box 7.

Confronting Global Water Risks in an Unprecedented Era

By C. Adam Schlosser

For most of the past decade, the annual *Global Risks Report* conducted by the World Economic Forum has identified impending water crises, extreme events, and the failure of climate-change mitigation and adaptation as three of the top five drivers of risk to the future sustainability and vitality of our global society and the environment. On one hand, these perceived risks underscore the importance and urgency that decision-makers are placing on environmental threats to societal resources, welfare and growth. However, they also convey an overall lack of confidence that any commensurate action will take place to prepare and secure critical resources and infrastructure for the future.

A Looming Water Accessibility Crisis

A case in point is accessibility to fresh water, which is compromised by: inhospitable terrain along some of the world's largest river basins, international conflict and flooding, as well as egregious mismanagement. Due to these factors and the limitations of current infrastructure, while the Earth's hydrologic cycle produces approximately 40,000 cubic kilometers of annual water flow in rivers, only about a third of this is extractable for human use. Therefore, the water flow from rivers that is globally "accessible" to humans amounts to approximately 13,200 cubic kilometers.

Given this current capacity of water accessibility, is the world inexorably heading toward a water resource crisis? To put this in perspective, for a nation to be regarded as "self-sufficient" for a modern standard of living under conventional uses of water resources, per capita annual water supply should not drop below approximately 1,700 cubic meters (Postel, 1997). With an estimated current population of over 7.5 billion, this amounts to a required global water supply of approximately 12,750 cubic kilometers (or 3.4 quadrillion gallons) for all nations to meet this level of self-sufficiency.

While still below the estimated "accessible" water supply from rivers, it is close to a commensurate value. Moreover, population is projected to surpass 8 billion by 2025, with much of the growth expected in underdeveloped nations of Africa—where it is likely that many people will aspire to live at standards enjoyed by developed nations. Assuming these trends and no global efforts to adopt more efficient water use, over the next decade the world will no longer have the capacity to sustain every human at modern living standards. By these measures, this constitutes an unprecedented global threat.

Risk Assessment and Response

While this threat calls attention to an important global perspective, it is hardly one that incites specific courses of action—whether mitigating or adaptive—at regional, basin or local scales. Several considerations factor into an assessment of water risk. The regional and localized nature of the hydrologic cycle, river flows, and extreme conditions that cause drought and flooding factor heavily into the amount of water that is ultimately "accessible" at any given place and time. Predictions of trends (whether natural or human-forced) in the mean, variance and extremes are uncertain, and therefore necessitate a risk-based approach. And within any given basin, the prognosis of water demands across the agricultural, municipal, industrial and energy sectors are confounded by complex interrelationships that include: population change, migration, intensification and expansion of land cultivation, irrigation, urbanization, standard of living, diet, economic growth and geopolitical conflict.

In many basins around the globe, severe water-scarcity challenges have already emerged or are evolving. Humans have shown a remarkable ability to manage and adapt to these situations, but largely in a response-driven or reactionary fashion. Despite the complexities noted above, many of these water scarcity issues have been confronted through the construction of large-scale storage, diversions and/or inter-basin transfer projects. These projects have come at high cost. Yet as history has demonstrated, insufficient information on historic river flow as well as egregious misallocations of water shares can lead to water-scarcity conditions in surrounding basins that are more severe than those within the basin of concern.

To add further challenge and risk in reactionary measures, regionally uncertain projections of future climate change and variability, as well as changes in socioeconomic stressors and political drivers, can veer a short-term "low-risk" solution toward one likely to be ineffective.

Quantitative assessments of risk that identify the most likely as well as most damaging trajectories, and note regions and sectors that are at low (or lowered) risk, are needed. This may provide greater confidence and identification of proactive (or prediction-based) risk-reduction measures that have the greatest likelihood of success.

Modeling Advances

Identifying large-scale adaptive and mitigating measures that most effectively reduce future risks requires predictive tools that describe the important sectors of the coupled human-Earth system and their interactions. In the past decade, the research community has made substantial advances in the ability to observe, analyze, simulate and predict the behavior of and interconnections among natural, managed and built environments. These modeling improvements have provided unprecedented spatial resolutions and representations of environmental processes. Combining today's Earth-system models with the growing volume of observational data requires machine-learning methods to better elucidate the complex relationships among the natural and human sectors and improve model algorithms. These models must be computationally efficient to comprehensively assess risk, and project myriad plausible pathways of the coupled human and Earth's systems. These pathways include the natural cycling of water in the Earth's climate system as well as managed water with interconnections between the municipal, industrial, energy and agricultural sectors.

Research Frontiers for Water Risk

Multi-sectoral model assessment of the fate of alpine seasonal snowpack and glacial extent, the sustainability of groundwater resources and the quality of water resources are key research frontiers for issues of water risk.

Higher-resolution models are becoming increasingly adept at capturing the orographic details of critical snow and glacial water resources in alpine areas. For many regions of the world, understanding the risk of seasonal changes or accelerated depletion of these climate-sensitive alpine water-storage zones will be crucial to supporting the sustainability of populations that rely on the meltwater resource. In regions where surface flows are insufficient to meet water demands, groundwater is often extracted at rates that exceed the natural rate of recharge. Recharge rates can be affected by human activities that either interfere with or intercept the natural drainage and flow of water that would eventually make its way to the water-table depth. The extent to which expanding and intensified human activities directly (e.g. pumping) and indirectly (e.g. human-forced climate change) affect the fate of groundwater will factor heavily into the prognosis of risk to water supply over the coming decades. Lastly, all water utilized in human activity is exposed to some degree of risk regarding its quality, especially for agricultural, industrial and municipal water-use sectors. This issue becomes increasingly problematic within and across basins where downstream reuse is substantial.

An additional and important intersection of these frontiers occurs between water quality and groundwater. As coastal communities and cities grow and become more densely populated in tandem with sea-level rise, groundwater may become more brackish and unsuitable for consumption. These issues can only be adequately assessed with full consideration of groundwater and the complex details of saline intrusion along coastal seawaters. Moreover, groundwater quality is substantially affected by the rates of extraction and recharge.

To best address issues of water risk within a changing and increasingly complex world, we must not continue to rely only on diagnosis and reactionary measures. Multi-sectoral modeling efforts are beginning to provide the risk-based prognoses necessary to explore solutions across a range of possible outcomes. By quantifying what/where/who are at the greatest risk, effective mitigation and adaptation options can be identified.

C. Adam Schlosser is a Deputy Director of the MIT Joint Program

Food and Agriculture: Challenges and Implications

Our EPPA model is an economy-wide model, and hence includes agricultural projections. The resolution of our standard model includes crops, livestock and output of the food sector. As part of the IGSM framework, the EPPA model is used to make projections of greenhouse gas emissions and other pollutants that lead to environmental change, but there is no feedback of climate change on the economy and various economic sectors in its standard format. We report here the agricultural projections consistent with our baseline EPPA model projection without feedback of climate change, and include some speculative analysis indicating how climate change might affect these projections. The climate impact estimates are illustrative, and not fully consistent with the baseline Outlook projections.

Agriculture, like energy, will need to undergo major transformations in the coming decade as demands grow. These include structural, value-chain and technology transformations (**Box 8**). While the pace and direction of these changes are uncertain, they will be essential, especially for the successful development of lower-income countries. While we do not model these transformations explicitly, we impose continued productivity improvements for land (i.e. yield increases) and increasing productivity of labor, capital and energy.

Our projections show that at the global level, from 2015 to 2050, the value of overall food production increases by about 130%, crop production increases by 75%, and livestock production by 120% (**Figure 31**) We have incorporated in our EPPA model declining income elasticities of demand for food as income rises, approximating recent econometric evidence and projections (Gouel and Guimbard, 2017; Fukase and Martin, 2017). These recent studies indicate that the income elasticity for final demand for crops will approach zero in most regions, implying that demand would grow only with population. Our estimates are consistent with that projection, but the 75% increase in production of crops is more than twice the increase in population of 32% from 2015 to 2050 in our projection. That's because of the more rapid increase in livestock production, to which crops are an important intermediate input. Food production in billions of dollars is much

Box 8.

Agriculture's Three Transformations

By Mark W. Rosegrant

Agriculture in the developing world is undergoing three major transformations: the Structural Transformation of Agriculture, which is far along in most of the world; the Value Chain Transformation, which is moving rapidly, but still has a long way to go; and the nascent Advanced Technology Transformation. How these transformations play out in developing countries will have a major impact on growth and development in each country's agriculture sector and entire economy.

The Structural Transformation of Agriculture

Due to the large share of agriculture in the economy in early stages of growth, the increased agricultural growth driven by productivity improvement and increased use of inputs is a force for overall economic development. Rapid growth in agriculture frees up labor and capital for the nonfarm economy, maintains a downward pressure on food prices while keeping pace with growing food demand and key primary inputs for agroindustry, contributes to foreign exchange earnings (through reduced agricultural imports and increased agricultural exports), and provides a buoyant domestic demand for nonfarm goods and services (Johnston and Mellor, 1961; Johnston, 1970). These results of agricultural growth lead to rapid growth in the rural nonfarm economy and the transformation of the urban-based economy (ibid.).

As agricultural-led economic growth proceeds within a country, it results in the structural transformation of the economy. This process entails a) a declining share of agriculture in GDP and employment, b) a rural-to-urban migration that stimulates urbanization, c) a rising modern industrial and service economy, and d) a demographic transition from high birth and death rates common in poor rural areas to lower ones associated with better health standards in urban areas (Barrett *et al.*, 2010).

An important driver of structural transformation is induced technical change: agricultural technology innovation and adoption that is often biased toward saving the limiting factor of production—land or labor—as the relative scarcity of land or labor endowments is reflected in the change in their relative prices (Hayami and Ruttan, 1970). Alternative agricultural technologies are developed (and adopted by farmers) to facilitate the substitution of relatively abundant (cheap) factors for relatively scarce (expensive) factors (Ruttan, 2002). Agricultural economists have commonly viewed mechanical technology, which substitutes power and machinery for labor, as "labor saving" and biological and chemical technology as "land saving." But increasingly, biological technology is also labor saving. Bt-cotton, genetically modified to produce the naturally-occurring *bacillus thuringiensis* soil bacterium for enhanced pest resistance, has been labor-saving in India, and genetically engineered soybeans are strongly labor-saving technologies in Brazil, reducing the demand for labor in agriculture (Diao *et al.*, 2016). Even when there is underemployment in much of the agricultural year, employment shortages in peak seasons such as land preparation and harvesting can induce farmers to reduce their reliance on labor. Migration to cities or to rural nonfarm work is also caused by labor leaving farms when declining farm sizes cannot support adequate income.

However, countries that develop later are at a disadvantage in the structural transformation. Diao *et al.* (2017) show that growth-enhancing structural change in Africa appears to have come at the expense of declining labor productivity growth in the more modern sectors of the economy. They argue that the forces that are promoting structural change in Africa originated on the demand side, either through external transfers or increases in agricultural incomes, rather than through productivity growth. In contrast to Asia, structural change was the result of increased demand for goods and services produced in the modern sectors of the economy rather than productivity improvements in these sectors. This structural impediment to continuing transformation is exacerbated by the slow demand from the rest of the world for primary goods from the developing world. Overcoming this disadvantage could be facilitated by the value chain and advanced technology transformations.

The Value Chain Transformation

Value chains in developing countries have undergone significant transformation over the past 50 years, a process that has accelerated in the last two decades (Reardon, 2016). During the 1960s and 1970s, government-owned parastatal organizations in many countries assumed the role of procuring and selling food. Beginning in the early 1980s, implementation of structural adjustment policies reduced the direct government role in supply chains in much of Asia and liberalized supply chains.

Reardon (2016) showed that liberalization and privatization of supply chains resulted initially in re-fragmentation of the system, with the rise of small and medium enterprises (SMEs). Following this rapid proliferation of SMEs has been the more recent trend of consolidation of small businesses into larger ones. Market liberalization and privatization of parastatals drew big foreign direct investment in the 1990s and 2000s in retail (supermarkets, fast-food chains) and processing, with inroads into logistics and wholesale services. Large-scale retail and processing firms in developing regions have modernized their marketing and procurement systems to cut costs and increase efficiency, and to meet the

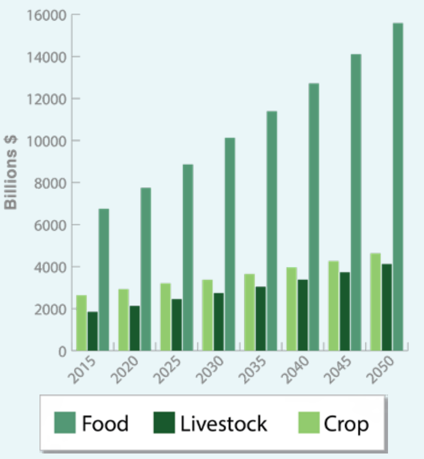

Figure 31. Global crop, livestock, and food production

greater than livestock and crop production because it includes value-added and other inputs used in producing food. These economic projections of food production are not the same as efforts that project tons or calories of food production, because of the increasing value-added component of food production as income rises, one of the major transformations discussed in Box 8.

We see evidence of the changing structure of agriculture in our projections for the *Developed*, *Other G20* and *Rest of the World* regions (**Figure 32**). Notably in the *Developed* region where incomes are the highest, the value of food production is much greater than that of livestock and crop production, reflecting the added value and "non-food" inputs that go into food production in this region. In comparison, in the *Rest of the World* region, values for crop and livestock production are nearer the total value of the food production sector, because there is less processing and some of the livestock and crop production go directly to final consumption rather than through a food production sector. The *Other G20*, a group of countries generally wealthier than the *Rest of the World* region but not as wealthy as the *Developed* Region, is an intermediate case. Also notable is that crop production is much larger than livestock production in the *Rest of the World* region and continues to grow at a fairly substantial rate, so that crop production remains greater than livestock production through 2050. In both the *Developed* and *Other G20* regions, crop production is larger than livestock production in 2015, but live-

quality, food safety and phytosanitary standards demanded in today's markets. This transformation appears to be improving food security for cities by reducing marketing margins, offering lower consumer prices and increasing the quality and diversity of food (Reardon *et al*., 2014). But evidence is mixed regarding the impact on farmers. Available data shows that larger farmers with higher assets have the highest participation rates in the transformation. Farmer participants in transformed systems can experience a net income gain and risk reduction, relative to those in traditional markets. Gains can come both from rewards for quality differentiation and from a price premium for controlling for quality (Reardon and Timmer, 2012). But those farmers who are left out may lose.

The structural and value chain transformations, which both drive and are driven by urbanization and income growth, are contributing to rapid change in diets. Populations in those countries undergoing rapid economic growth and transformation are experiencing the most rapid nutritional transition. Beginning in Asia, but increasingly for the rest of the developing world, diets are shifting away from staples and toward livestock and dairy products, vegetables and fruit, and fats and oils. Globalization and the consequent global interconnectedness of the urban middle class is another driving force behind the convergence of diets. The rapid spread of global supermarket chains and fast-food restaurants is reinforcing these trends. Income growth in developing countries is driving particularly strong growth in per capita and total meat consumption, which in turn induces strong growth in feed consumption of cereals, especially maize.

The Advanced Technology Transformation

Total factor productivity growth in agriculture has been strong in much of the world. Now rapid technological change outside of agriculture is creating new potential for technological change within agriculture. Disruptive new technologies are likely to be strongly labor-saving, which will be beneficial where agricultural labor is becoming scarce. Advanced technologies are also likely to create economies of scale in agriculture that could increase pressures to consolidate land ownership or the operational size of farms. Value chains will also be fundamentally influenced by these advanced technologies, with the potential for significant reduction in post-harvest losses, and fundamental changes in contract farming. How these technologies play out will also influence employment and rural-urban migration. These advanced technologies will have complex impacts for farmers, value chains, the agricultural sector and beyond.

Technologies coming on line include advanced sensors that allow full tracking of food from source to final use and monitoring of quality throughout the chain, thereby increasing value premiums and reducing losses; second-generation precision agriculture, using satellite imagery and advanced sensors to optimize intra-field returns on inputs while preserving resources at larger scales; and agricultural robots to automate agricultural processes such as harvesting, fruit picking, ploughing, soil maintenance, weeding, planting and irrigation (Zappa, 2014). Gene editing has the potential to generate rapid advances in crop breeding if this technique is spared the heavy regulatory burden of GMOs. While these technologies will be adopted more rapidly in developed countries, movement can already be seen in developing countries, often with cheaper, smaller-scale versions. The impacts in developing countries will depend on the development of scale-appropriate technologies and policies. Advanced technologies could give a big technological advantage to agriculture in developed and middle-income countries unless appropriate policies and investments are in place in lower-income countries.

Policies and investments will be critical to leveling the playing field so that developing countries can take advantage of advanced technologies. Enhanced rural infrastructure investments are needed to improve access to markets, information, risk insurance, credit and inputs. These investments include rural roads, irrigation, cell phone towers, markets, and cold storage and processing facilities, many of which will require private sector engagement. Legal and regulatory reforms, including implementation of science-based biosafety regulatory systems, are needed to reduce hurdles to approval and release of new technologies, and to remove barriers to foreign direct investment. Improved economic policies are also needed. Subsidies that distort production decisions and encourage overuse of inputs, including fertilizer, energy and water subsidies, should be phased out. Savings from subsidy reductions should be invested in productivity-enhancing agricultural research and development, and in non-distorting income support to small farmers to ease the transition from subsidies. Establishment of secure land and water rights and markets for those rights would allow increases in operational farm size and efficient contracting of farming services, to facilitate the economies of scale that the new technologies will create.

An age of transformative agricultural technologies is upon us, and will significantly impact agricultural growth, but the broader impacts of these advanced technologies in developing countries remain uncertain. It is essential to assess these trends and develop policies that will help to fully realize the potential of advanced technology in smallholders' or transition farming systems in developing countries to support the ongoing agricultural and economic transformation.

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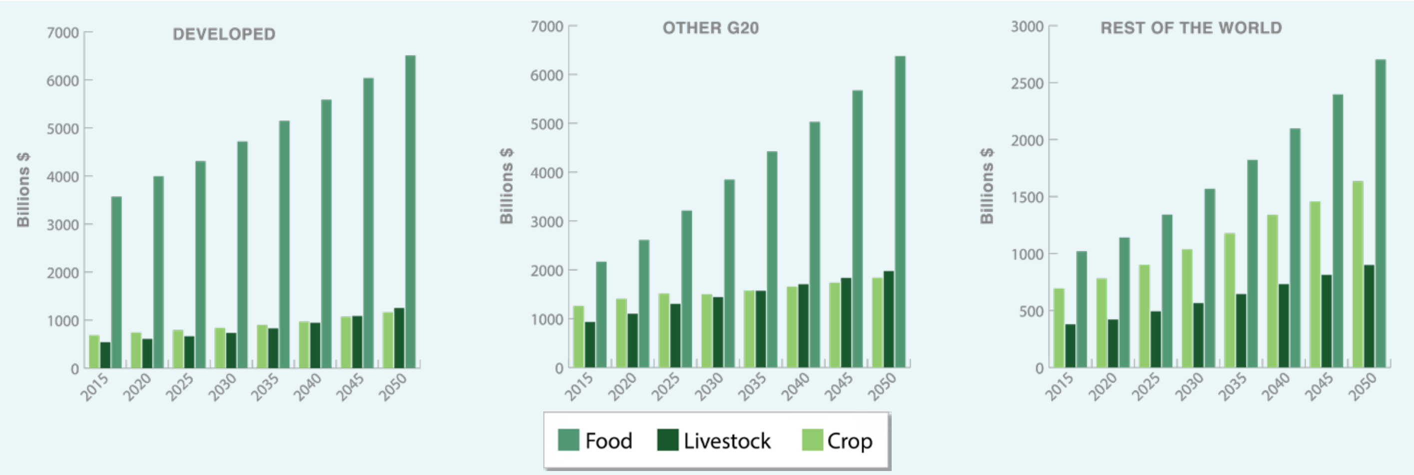


Figure 32. Regional crop, livestock, and food production for *Developed* (left), *Other G20* (center), and the *Rest of the World* (right).

stock production grows faster and exceeds the value of crop production by 2050. The faster increase in food production is particularly evident in the *Other G20*, a result of increased value-added and non-food inputs in the food production sector.

Agricultural commodity and food price indices show gradual increases through 2050 as a result of growing demand. To highlight the importance of yield improvements, we show price projections under our base assumption that land productivity in all uses increases by 1% per year, and an alternative case where it increases at 2% per year (**Figure 33**). Not surprisingly, more rapid productivity growth means smaller price increases. We see a general pattern of moderate increases in crop prices, larger increases in forest product and livestock prices, and fairly small increases in food prices. This is a consistent and expected pattern. Since land is the scarce factor in the production of agricultural commodities, a reason for the difference in crop and forest product prices is that land is a larger input share in forest products. There is a much larger share of labor, capital and intermediate inputs in crop production, and so that moderates the increase in crop prices. The explanation for greater livestock price increases is slightly different. Crops are an important input into livestock production, and so their price increase affects livestock prices. But grazing is also an important input, and hence increases in the cost of grazing land also drives up livestock prices. Despite these rising farm-gate prices for crops and livestock, the food price index increases very little. This is because the cost of other inputs constitutes the larger share of final consumer food costs, and so the trends in basic commodity prices have a relatively small effect.

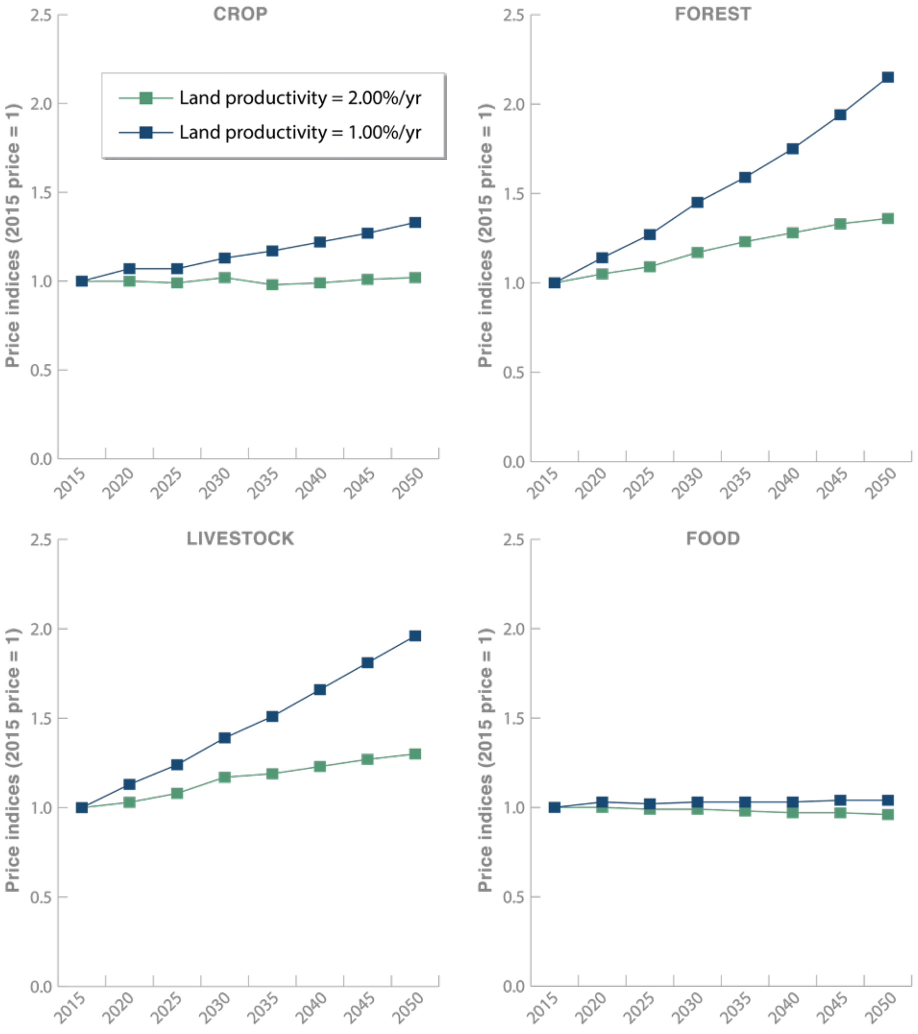


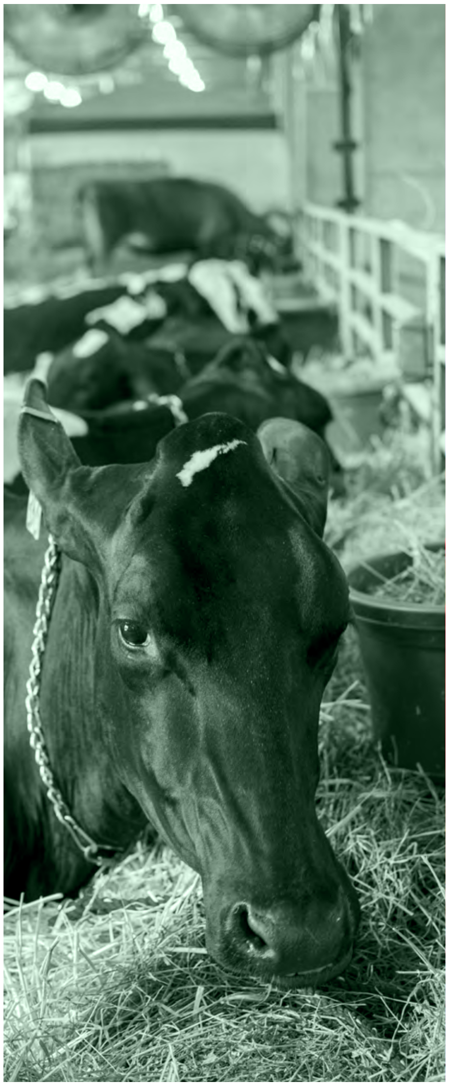
Figure 33. Price indices for crop product (top left), forest product (top right), livestock product (bottom left) and food product (bottom right).

Land productivity (i.e. yield) improvements in agriculture are uncertain. Some analysts see evidence of yield plateaus after decades of ever-increasing yields, or would characterize yield increases as linear rather than exponential, and see biological limits to crop yields. Others note that yields in many parts of the world are well below what is achieved under "best practice" and see biotechnology as a revolution that will result in much higher yields. Climate-change impacts on yields are also highly uncertain, but according to the

IPCC most studies suggest that such impacts could decrease yields globally.

We have not yet seen robust models that fully and consistently account for climate impacts for all regions of the world, building up from spatially resolved effects on yields and consequent impacts on agricultural markets, food security and the economy. The closest approximation to these are globally gridded crop models (GCCMs). They provide estimates of yield changes for major crops, simulating the crops for every land-based grid cell, whether or not the crop is grown there now or would be grown there in any likely future. Even where some crops may do well, they would need to compete with other crops and other uses of that same land. In our *2016 Outlook*, we presented and reviewed results from emulators of several major GCCMs. We noted that they often do not project current yields with much accuracy. They also do not cover impact on all crops or on livestock. An agricultural modeling intercomparison project brought together various economic models and crop models to provide comparison simulations (Valin *et al.*, 2014).

The other approach used to assess the effects of climate change on agriculture is to review the many detailed studies that focused on different areas of the world and different crops. The IPCC provides the most authoritative review but has limits: Crops are evaluated under completely different assumptions, climate scenarios and crop models. Some of these analyses include many environmental stresses and changes, while others represent far fewer; some address adaptation or different potential adaptation options. As a result, it is unclear where estimates for different regions or crops reflect different underlying modeling approaches as opposed to fundamentally different impacts of climate change.



For example, a study in one region using a crop model that responds more negatively to climate, includes fewer adaptations or uses a severe climate change assumption may show very negative impacts for that region. Assessing the same crop in another region with a different crop model, more adaptation or a less severe climate outcome may show only modest yield impacts. Looking just at the estimated yield impacts, one might conclude that the first region was likely to be more severely affected by climate change. Yet if the same crop models, climate scenarios and other assumptions were applied consistently to both regions, that conclusion could easily be reversed.

Moreover, while some countries and regions within countries have been extensively evaluated, many others have been ignored, and only a subset of crops has been evaluated in any one region. Estimated yield effects range from very negative to positive.

A summary of all studies by the IPPC (Porter *et al.*, 2014) shows a modal value (all crops, all regions) of 0 to -2.5% yield loss per decade, with a significant portion (40%) of studies showing no significant impacts or an increase in yields, and ~20% of studies showing losses of 5 to 10% per decade. While the IPCC describes a variety of

impacts on livestock, it provides few actual estimates of the effect on livestock productivity.

Recognizing the limitations of the IPCC review, we have nonetheless deduced a set of crop and livestock productivity effects, loosely informed by yield studies reported in the IPCC Box 7.1 (Porter *et al.*, 2014). Rather than show no impact on crops not reported, we have assumed an average impact on these crops, and have imposed an overall effect on pasture and livestock productivity. The specific assumptions and their consequences are reported in **Box 9**. These assumptions are subjective, and while within the range of studies presented, intended to be merely illustrative. Moreover, the climate scenarios are not consistent among the studies or with our Outlook projections, although they would probably fall within the range of the climate outcomes we project. Overall, the effects on commodity prices, production, land use and the economy are relatively modest. The IPCC (Porter *et al.*, 2014) modal yield impacts of 0 to -2.5% loss per decade, if at the high end of the range, would be equivalent to an annual rate of yield decline (2010–2050) of ~0.25%. Earlier we provided results for annual yield increases of 1% and 2% per year, and so if we saw this amount of loss, it would be only potentially erasing ¼ to ⅛ of these possible yield gains, with losses that in principle could be made up by more aggressive efforts to increase yields.

Given the implications for commodity prices of those changes, the relatively small overall commodity price impacts of these yield impacts is not surprising. Climate change may be more disruptive than such a calculation indicates, hitting some regions much harder and creating unexpected variability and extremes. One implication of our simulations is that broadly negative climate impacts on yields and livestock productivity will put more pressure on land-use change and increase CO_2 emissions, thereby creating a (modest) positive feedback on climate change.

Box 9.

Potential Climate Effects on Agriculture

We deduced a set of comprehensive productivity effects of climate change (affecting all crops and all livestock) intended as an interpretation of central estimates for possible 2050 impacts that appear in the literature reviewed by the IPCC (relying on Box 7.1 in Porter *et al.*, 2014). We linearly increased those productivity shocks, starting in 2015 at 0 and rising to the reported changes (**Figure 34**) by 2050, for specific crops and livestock types using a new, more disaggregrated version of the EPPA model. A novel aspect of this approach is that cropland (or other land types) can be created from other land uses, which is one adaptive response to yield declines. It also simulates substitution of other inputs to make up for yield losses and regional shifts in production and agricultural trade. The productivity shocks we developed required extrapolation well beyond the specific regional and crop estimates reported in the IPCC. Few specific productivity impacts on livestock are available, but the known effects of heat on productivity are described in the IPCC—we assume a uniform productivity shock of -10% on all livestock types in all regions, a uniform -5% productivity impact on pasture, and no impact on forestry. The IPCC yield estimates are largely limited to major grain crops, including soybeans. We calculated an average yield shock for each region for reported crops, and assigned that average shock to all other crop types. Soybeans (oilseeds) are the only crop for which studies tended to show positive effects in some regions. Maize and wheat tend to have larger yield losses. There is some reflection of the observation that temperate/poleward crops are less negatively affected (e.g. USA, CAN), while tropical and subtropical regions (e.g. LAM, REA) are more negatively affected, but there are exceptions (or the pattern is very weak and/or obscured by the large regional aggregation or the lack of many studies for the region). The IPCC reported multiple studies for the same crops in some regions—we chose mid-range estimates or those most relevant to climate change we project as likely by 2050.

We simulated the crop yield and livestock productivity impacts on agricultural production, the economy (measured as welfare change), and emissions from land-use change, and report them for the three regional groups used throughout this Outlook and as a global average (or total as appropriate) (**Table 3**). We also report global average impacts on commodity and food prices (**Figure 35**). Global production is generally reduced by less than 5% from the baseline projection with no climate change, with the exception of chicken & pork. Generally, the production effects are less than the direct yield or productivity impact because of inelastic demand and rising prices that encourage various adaptive responses that partially make up for the direct yield losses. The overall global welfare loss is -0.7%, generally smaller than the production effects because the welfare measure includes all goods—food and agriculture are a relatively small share of consumption.

The *Developed* region sees production increases for many agricultural products, resulting from comparative advantage changes. While these temperate countries often show yield losses, these losses are on average less than in other parts of the world. Welfare effects are also smaller, with these countries again benefiting from comparative advantage change in yields and the fact that the direct cost of commodities is a much smaller share of final consumption due to (1) higher overall income, and (2) greater expenditure on other goods generally unaffected by the simulated yield and productivity impacts. The *Other G20* countries are spread across many different climatic zones and experience a mix of impacts with production effects often near the global average. The *Rest of the World* region generally experiences larger (negative) production effects, losing directly from yield and productivity effects and also due to their loss of comparative advantage.

Global average prices for major crops and forest products generally increase by 4 to 8% by 2050 above the baseline forecast with no climate change. The forest products price increases more sharply in later years, reflecting the fact that there is a fairly significant conversion of managed forest land to other uses (crops and pasture). We did not apply a direct yield effect on forest productivity, and so all of the impact is a result of land price pressures. The effects on global livestock product prices end up at around a 25% increase by 2050. Livestock costs are affected by rising feed-grain prices, lower pasture productivity and the direct productivity effects we have assumed. The food price effects are on the lower end of all the price impacts, about a 4% increase by 2050, because the farm-gate commodity costs are only a small part of food costs.

The land-use changes result in an increase of 1875 Mt of CO_2 emissions accumulated over the period 2015–2050, averaging 53 Mt per year over that period. Compared to the fossil energy emissions of ~35,000 Mt per year, this represents a small additional contribution to total greenhouse gas emissions, but has an obvious positive feedback—e.g. greenhouse gas emissions, the cause of global warming, are increased by the warming trend as a result of land-use change. Cropland and pastureland areas increase, mostly in the *Rest of the World*, even though production has decreased because yields and productivity are lower. Again, we emphasize that the various yield and productivity shocks we have simulated required significant extrapolation (to broader regions, and to other agricultural commodities) to more comprehensively treat the livestock and crop sectors than were available in the IPCC reviewed studies.

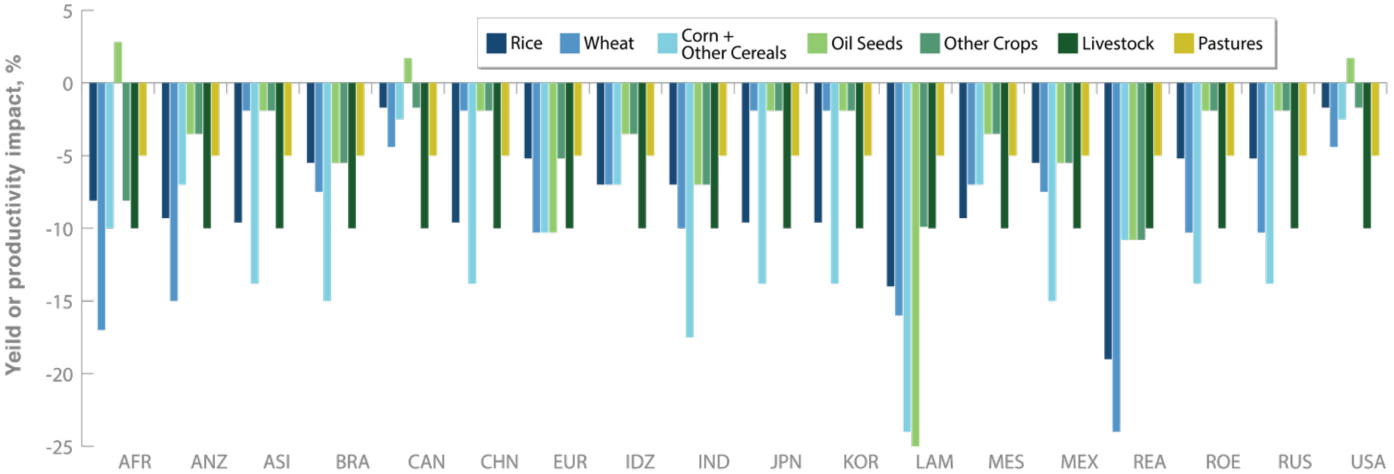


Figure 34. Crop, pasture and livestock productivity (yield) impacts of climate change in 2050

Table 3. Impacts from yield shocks on agricultural production, welfare, land-use areas and carbon emissions in 2050

		Developed	Other G20	Rest of the World	Total
% Change in Output	Rice	2.1	-2.5	-6.4	-3.2
	Wheat	1.3	-2.4	-3.7	-2.0
	Corn & Other Cereals	3.7	-3.5	-2.1	-0.9
	Oil Seeds	2.8	-1.7	-7.6	-2.1
	Sugar Cane & Beet	0.1	-2.4	-3.5	-2.6
	Vegetables & Fruits	0.8	-2.5	-1.8	-2.0
	Fiber Plants	-1.2	-3.3	-0.8	-2.1
	Other crops	1.7	-2.1	-3.5	-1.4
	Cattle & Ruminants	-2.9	-4.4	-5.8	-4.4
	Chicken & Pork	0.0	-6.1	-5.3	-5.2
	Other livestock products	-1.2	-5.2	-5.1	-4.5
	Forestry	1.2	-0.5	-11.8	-2.3
	Food	0.6	-2.4	-3.1	-1.4
	Welfare	-0.1	-1.6	-1.3	-0.7
Land use changes	Cropland (Mha)	0.6	19.5	50.7	70.7
	Cropland (%)	0.1	2.9	7.2	4.0
	Pasture (Mha)	0.4	-1.9	18.6	17.1
	Pasture (%)	0.1	-0.5	1.6	0.9
	Managed Forest (Mha)	-1.0	-16.3	-65.5	-82.8
	Managed Forest (%)	-0.5	-7.1	-25.8	-12.3
	Natural Forest (Mha)	0.0	-0.8	-3.7	-4.6
	Natural Forest (%)	0.0	-0.1	-0.5	-0.1
	Natural Grass (Mha)	0.0	-0.5	0.0	-0.5
	Natural Grass (%)	0.0	-0.1	0.0	0.0
	Emissions 2015–2050 (Mt CO_2)	49.9	1050.7	774.1	1874.7

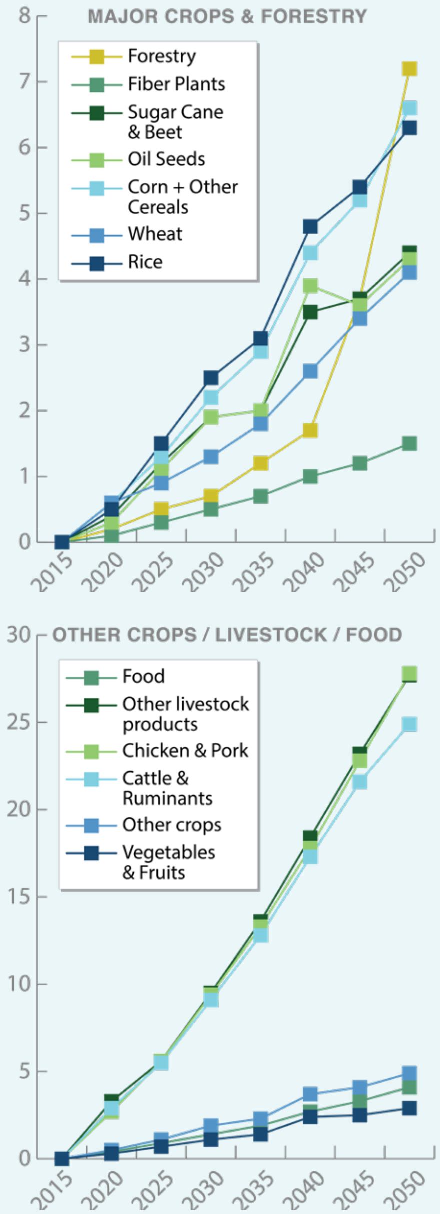


Figure 35. Impacts on prices of major crops and forestry products (top) and other crops, livestock and food (lower), global average % change from baseline projection

Prospects for Meeting Short-Term Paris Commitments

We have invited experts on policy developments around the world provide their perspectives on how well key countries and regions are progressing in fulfilling their Paris pledges. They report on some bright prospects, including expectations that China may exceed its commitments and that India is on a course to meet its goals. But they also observe a number of dark clouds, from U.S. climate policy developments to the increasing likelihood that financing to assist the least developed countries in sustainable development will not be forthcoming at the levels needed.

European Union: Achieving Supranational Consensus

***Michael Mehling**, Deputy Director of the MIT Center for Energy and Environmental Policy Research; Professor at the University of Strathclyde*

Europe has styled itself a climate leader since the earliest days of the climate regime, and has traditionally endorsed binding targets and timetables for greenhouse gas mitigation, coupled with a robust compliance regime. Although the Paris Agreement—with its flexible, decentralized approach—marks a departure from the regime architecture favored by the EU, the Nationally Determined Contribution (NDC) submitted for its 28 member states ranks among the most ambitious, requiring emissions to decline 40% below 1990 levels by 2030. Major emitting industries and the power sector are subject to a declining emissions cap under the European Union emissions trading system (EU ETS), the world's first—and still largest—cross-border carbon market. More targeted measures have been adopted for a number of other sectors, such as transportation, households and land use.

Experience under this policy portfolio has not always been positive, and has included adverse policy interactions and other unintended consequences. For the time being, however, the EU can nonetheless claim a successful track record: it achieved its Kyoto Protocol commitment ahead of schedule, reducing emissions by more than 20% since 1990. More recently, emissions have risen again with growing energy demand and industrial output, jeopardizing achievement of the 2030 pledge and the long-term target of an 80–95% reduction by 2050.

To sustain past climate leadership and progress toward decarbonization by midcentury, therefore, Europe will need to strengthen its policies, even while the political atmosphere in Brussels and in Europe's national capitals has become more challenging. Nationalist and EU-skeptical movements are on the rise in several member states, with Britain's EU withdrawal only the most visible manifestation. In a supranational process built on member-state consensus, these threats to the European integration project make it more difficult to advance climate action. Some newer member states—including a political alliance of Poland, Hungary, the Czech Republic and Slovakia—have repeatedly blocked or weakened climate policy reforms. Even traditionally progressive member states have seen internal pressure from domestic constituencies weaken climate policy support. In Germany, for instance, politically influential car manufacturers have opposed tighter performance standards.

European climate action is also increasingly entwined with other policy agendas and areas of policy reform. Continued growth of renewable energy across Europe, for example, is hampered by uncertainty about the future design of the European electricity market. Similarly, policies to lower the emissions from agriculture and forestry are inseparably linked to further evolution of the Common Agricultural Policy (CAP). Most importantly, perhaps, attempts to bolster the anemic carbon price under the EU ETS—a key to incentivize fuel switching from coal to natural gas in power generation—have been held back by concerns about energy security and impacts on mining communities. Nevertheless, progress—however slow—remains possible, as indicated by the recent agreement to strengthen the carbon market for the period beyond 2020.

It remains to be seen whether climate ambition will also prevail in similar negotiations on energy efficiency and renewable energy, including in transport; and whether the emerging energy governance framework will favor accelerated decarbonization. For the foreseeable future, developments on other fronts, including questions around the bloc's future after Brexit, will take precedence. With such existential matters at stake, convincing euroskeptic voters of the benefits of EU integration will likely depend on positive messages about economic growth and employment rather than on additional carbon constraints. With success on these economic fronts, however, the EU may regain the common voice and aspiration to again lead by example.

USA: Dark Clouds, Silver Linings, Red Flags and Hail Mary Passes

__Kenneth Kimmell__, President of the Union of Concerned Scientists, a science-based advocacy group headquartered in Cambridge, MA

The current U.S. response to the challenge of global warming is a complex amalgam of dark clouds and red flags, silver linings and Hail Mary passes. The dark clouds and red flags are the Trump administration's rejection of a federal role in addressing climate change, and an effort to tilt the playing field in favor of carbon-intensive energy sources such as coal. The silver linings are continued cost reductions and market penetration of renewable energy, and the leadership of some states, cities and businesses to keep progress going. In the Hail Mary category, I would include the litigation filed by numerous cities and counties against major fossil fuel companies and a carbon fee and dividend proposal by establishment Republicans, with significant corporate support. These elements combine to cast great doubt over whether the U.S. will meet its Paris pledge to reduce greenhouse gas emissions 26–28% below 2005 levels by 2025.

Dark Clouds

The Trump administration has moved with ferocity and vengeance to undo almost everything the Obama administration did to address climate change. The most important actions include the pledge to withdraw from the Paris Agreement, and rollbacks of three key regulations—the Clean Power Plan, which limits carbon dioxide from power plants; limits on methane emissions from oil and gas drilling operations; and fuel-economy standards for cars and trucks. All three of these key rules are in the process of being severely weakened or even eliminated through executive action, and it is unclear what, if anything, the administration will propose to replace them. Of course, these rollbacks will face court challenges, so their ultimate fate is unknown.

Red Flags

In addition to rolling back regulations, the Trump administration is attempting to manipulate energy markets to favor coal and nuclear. It has claimed that there's a national emergency that requires uneconomical coal and nuclear power plants to remain open, by such measures as ordering regional transmission organizations to buy more power from these sources. The legality of this gambit is highly questionable, and has drawn opposition from consumer protection interests, natural gas and renewable energy suppliers, environmental groups and traditional economic conservatives who disfavor government picking winners and losers. However, if successful, this effort, as well as tariffs recently placed on foreign manufactured solar panels, may slow down the remarkable progress in renewable energy expansion.

Silver Linings

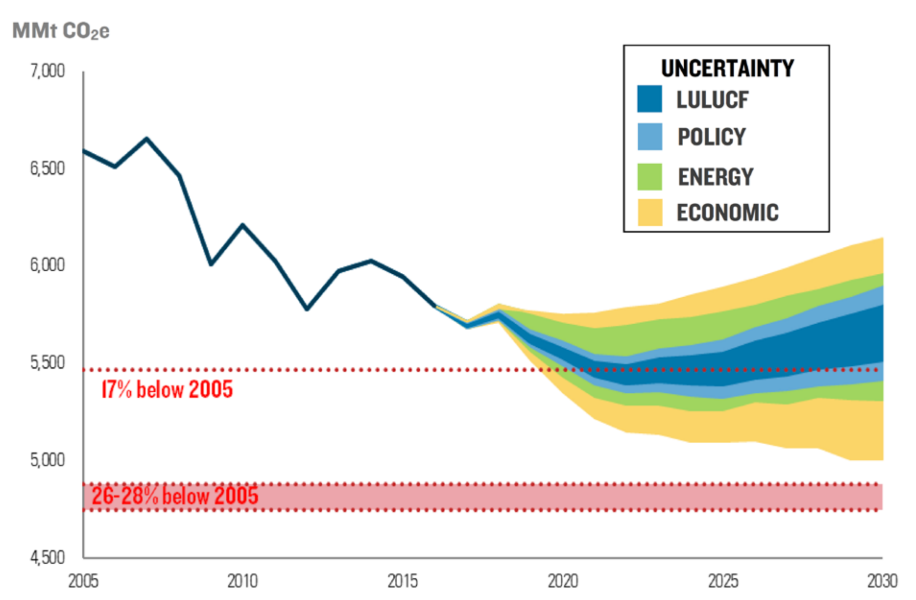
The administration's regulatory policy thus far has not slowed the closure of coal-burning power plants, or the penetration of wind and solar energy. These renewables are the biggest sources of new generating capacity, and major utility companies are continuing to support their expansion, especially of wind in the Great Plains and solar in the Southwest. Northeastern states such as Massachusetts, Rhode Island, New York and New Jersey are poised to launch a major new offshore wind industry on the eastern seaboard. Battery costs are plunging, making electric vehicles—and ultimately energy storage—increasingly cost-effective. And many corporations are investing in energy efficiency and renewable energy. All of these market factors are working to lower U.S. emissions.

Hail Mary Passes

There are two related efforts which face stiff odds but could be game-changers if they succeed. The first is a batch of lawsuits filed against major fossil fuel producers by the cities of San Francisco, Oakland and New York, and numerous counties in California, Colorado and Washington. These lawsuits seek to recover damages for the costs incurred by local governments to address impacts such as sea-level rise, storm damage, wildfires and droughts, all of which scientists are increasingly able to connect to climate change. These actions may create pressure for a legislative outcome. The other potentially game-changing effort is growing support for a carbon fee and dividend plan, which would impose a $40/ton price on carbon emissions with a price escalator, and return the revenues to the American people in an annual dividend check. The plan's backers claim that it would reduce emissions more effectively than Obama-era regulations. This proposal's fate is highly uncertain, and thus far no congressional Republican has embraced it.

Summary

When the Obama administration left office, it was widely understood that the U.S. was on a trajectory to meet its Paris Agreement pledge, although additional policies would likely have been necessary. Now, a year and half into the Trump administration, the goal seems significantly farther from reach. If the administration is successful in rolling back the key building blocks of the pledge, and insufficient reductions come from markets, state policy and corporate efforts, the U.S. very likely will fall short of its original Paris target—an outcome illustrated in **Figure 25**.



Source: EPA, Rhodium's US Climate Service.

Figure 25. Analysis of U.S. pathways by the Rhodium Group (https://rhg.com/research/taking-stock-2018).

South Korea: Controlling Emissions under Rapid Economic Growth

***Niven Winchester**, Principal Research Scientist at the MIT Joint Program on the Science and Policy of Global Change; Senior Fellow at Motu Economic and Public Policy Research*

South Korea has been developing its climate policy strategy since at least 2009, when it set a goal of reducing greenhouse gas emissions by 30% below its business-as-usual level by 2020 as a part of its Nationally Appropriate Mitigation Action (NAMA). This target was revised to 37% below BAU by 2030 as a part of its NDC under the Paris Agreement. Legislative authority is in place to use a combination of fuel-economy standards for light-duty vehicles, and a cap-and-trade system that would cover most of industry. While the broad outline of these policies has been established (with initial phases in place), and fuel-economy standards have been set through 2020, other details and timing of implementation to meet the 2030 target remain to be determined.

The South Korean president is considered a pragmatist, and his government is moving more aggressively on climate policy than the previous administration. Even so, the 37% reduction is from a baseline that is growing, and so the emissions cap for 2030 will be about the same as the NAMA goal for 2020; and some of the near-term policies have been relaxed to reduce the impact on industry. Climate Action Tracker (2017) estimates that current policies would result in emissions of 728–744 Mt CO_2 in 2030, well above the 536 Mt CO_2-equivalent NDC target. Moreover, Winchester and Reilly (2018) estimate that meeting the 2030 target would require a carbon price of around $90/ton of CO_2-e given the current outline of South Korean policy. That CO_2 price would be well above that in Europe, or estimates for the U.S. if the Clean Power Plan had gone forward. Even with the $90 price, South Korea's emissions would be at about its 2005 level, and well above its 1990 emissions. The nation is thus an example of the challenges facing middle-income countries with relatively rapid economic growth.

China: Enhanced Effort Supported by Air Pollution Control

***Valerie Karplus**, Assistant Professor of Global Economics and Management at the MIT Sloan School of Management*

Under the Paris Agreement, China's NDC includes several targets to be met by (or before) 2030. They include pledges: (1) to reach peak CO_2 emissions, (2) to increase its non-fossil share of primary energy consumption to 20%, (3) to reduce CO_2 intensity by 60–65% relative to 2005 levels, and (4) to increase its forest stock by 4.5 billion cubic meters compared to 2005. This NDC is a step up in degree and scope of ambition relative to China's first climate pledge in Copenhagen in 2009, which was to reduce CO_2 emissions intensity by 40–45% by 2020 relative to the 2005 level. Based on progress to date and expectations, this new pledge is consistent with broader policy directions in China and is likely to be met. The major open questions are how much sooner the country might reach peak emissions, and whether actions taken in the interim will lay a foundation for deeper decarbonization post-2030.

There are several promising signs that China will fulfill and even exceed its Paris pledge. First, since its first climate pledge on the international stage in 2009, China has advanced multiple policies and institution-building efforts to encourage low-carbon energy. Foremost among them is the introduction of national and provincial CO_2 intensity targets in its five-year plans, and a nationwide effort to develop industrial CO_2 accounts to support emissions trading, initially in regional pilots and eventually at a national scale (Jotzo *et al.*, 2018). Second, China's central government has taken steps to advance air pollution control in polluted urban centers, which has included the closure of small, polluting coal power stations and a broader shift to natural gas, measures which also help to reduce net CO_2. Third, industrial policy in China has increasingly emphasized research, development and deployment of clean energy technologies, from electric vehicles to solar to grid-scale energy storage. As a result of the combination of greenhouse gas targets and air pollution control agendas, government support for clean industries has increased, leading to growing production and an increasing presence in domestic and global (especially other developing country) markets. Accelerated climate policy ambition is welcomed and not opposed by these stakeholders, and connects well with several national narratives: leading on climate change, reducing pollution and dominating global markets for clean technology.

Nevertheless, headwinds to accelerated decarbonization remain. A large-scale shift to natural gas over the next 5–10 years will make deep reductions in CO_2 more difficult and costly in the long term. The expansion and operation of the electric grid has not kept pace with the new demands posed by large shares of intermittent renewables (Davidson *et al.*, 2016). And economic growth is still an important driver of national and local government decisions. Unless CO_2 emissions are decoupled from economic activity, which is unlikely to occur for a long time, even with a projected slowing of economic growth, upward pressure on CO_2 emissions will remain. Thus progress on climate change in China through 2030 will hinge on the perceived benefits of a range of actions that, taken together, may bring forward the timing of China's emissions peak. However, the nation is not yet well positioned to reduce emissions in absolute terms beyond the 2030 period.

India: Policy Foundations and Uncertainties

***Valerie Karplus**, MIT Sloan*
***Arun Singh**, PhD candidate at ETH Zurich*

India's NDC promises a reduction in CO_2 emissions intensity of GDP by 33 to 35 percent by 2030 from the 2005 level, and an increase in non-fossil based power to about 40% of cumulative installed capacity. While the electricity target is included as an independent component in India's NDC, in practice, it is designed to contribute to reducing emissions intensity.

A current question is what other policies should be implemented to support the country's NDC. India's climate policy does not include an economy-wide CO_2 price (although a tax of Rs. 400 [U.S. $6.30] per metric ton is levied on coal), but renewable purchase obligations (RPOs), similar to the renewable portfolio standards in the U.S., are in place for Indian states. Under the RPOs, revised targets set in 2016 require that the electricity mix include 17% renewable generation by 2019 and 8% solar generation by 2022 (both targets exclude hydropower). States in India have historically missed achieving their RPOs, and the current targets are also considered ambitious. Also, it is argued that renewables targets are not necessary to achieve India's emissions intensity targets, as other measures may be more effective (Tongia, 2016).

Another important element of India's broader energy and climate policy portfolio is the Perform, Achieve and Trade (PAT) energy efficiency scheme (Industrial Efficiency Policy Database, 2018). Announced in 2008 and administered by the Bureau of Energy Efficiency under the Ministry of Power, this market-based scheme aims to increase overall industrial energy efficiency by imposing mandatory energy consumption targets on firms in energy-intensive sectors and allowing them to trade energy saving certificates (ESCerts) to meet compliance obligations. The first phase (2012–2015) covered 478 facilities from eight energy-intensive sectors. Less efficient facilities face tougher targets than more efficient ones. Part of the rationale behind the program was to set up a cost-efficient system that avoided the political backlash of a "tax." This program further offers a foundation for supporting the country's overarching CO_2 intensity-reduction goal.

Willingness to accelerate climate-change mitigation efforts in India will depend on perceived costs and interactions with other human development goals. One-fifth of the country's population lacks access to electricity, and many households struggle to meet basic needs. Clean energy sources will only be adopted on a large scale if the costs are lower than conventional energy. Thanks to falling costs, solar capacity is expanding rapidly, with an earlier 20 GW target achieved four years ahead of schedule in 2017. The revised target for 2022 of 100 GW is very ambitious, however, and it raises the grid-level challenge of balancing a large intermittent resource.

Largely a service-based economy, India is also promoting development of its manufacturing industries, which is expected to contribute to the energy intensity of the economy. This shift in the sectoral composition of the economy will raise the importance of bringing clean energy sources online to replace and augment existing supplies. While India's CO_2 emissions performance since 2015 suggests that the nation can meet and even beat its Paris ambitions, progress over the next 15 years will hinge on the pace of energy-demand expansion, system-level challenges to integrating renewables, and the prominence of clean energy in the national development narrative.

The Middle East and North Africa: Challenges and Opportunities

***Mustafa Babiker**, economist at the Saudi Arabian Oil Company, Dhahran; Research Associate with the MIT Joint Program*

The Middle East/North Africa (MENA) is a diverse region characterized by fragile ecosystems and deep dependency on hydrocarbon resources, making it particularly vulnerable to the physical effects of climate change and the socioeconomic impacts of climate mitigation efforts. MENA is at once highly susceptible to climate risks such as water stress, desertification, sea-level rise and heat waves as well as to substantial losses in oil and gas revenues that could be incurred under a global transition to lower-carbon energy sources. These revenues, on average, account for 70% of government budgets and contributed more than 35% to the region's GDP in 2010.

Nonetheless, all MENA countries are participating in the Paris Agreement on climate change and have submitted NDCs. As the region consists largely of developing countries, most of these NDCs are broadly framed in the context of sustainable development and climate adaptation goals, with some commitments contingent on international financial support. For example, Morocco set an unconditional target of reducing GHG emissions by 13% from its business-as-usual level by 2030, and a stringent target of 32% conditioned on external financial support, and Lebanon pledged a 15% reduction below BAU, with an additional 15% reduction conditioned on international support.

To meet their Paris commitments, MENA countries aim to reduce GHG emissions primarily by deploying renewable energy technologies, boosting energy efficiency and shifting more of their fuel mix to natural gas. One promising factor is that MENA has a high potential for renewable energy technology deployment and use, especially when it comes to solar power with its increasing competitiveness. The shift toward clean energy production is gaining additional momentum due to the need to conserve hydrocarbon reserves, environmental and energy security concerns, and strategic positioning for a growing renewable energy market. Other factors supporting increased deployment of renewables include evolving climate policies, institutional capacity, energy price reforms and power-sector market conditions. At this time, the top-performing countries in the region in term of renewable energy deployment are Morocco, Egypt, Tunisia and the United Arab Emirates (UAE).

Despite this progress, considerable challenges remain. It will be no easy task to scale up renewable generation to the share of electricity generation pledged by several MENA countries, such as Morocco's target of 42% by 2020, or Algeria's pledge of 27% by 2030. The main hurdles to meeting such ambitious targets include transmission infrastructure, intermittency and storage requirements, economics, and availability of enabling regulations and institutions. Another key challenge is to provide affordable access to renewable electricity throughout the region. Identifying viable solutions will require thorough understanding and coordination among policymakers.

At a meeting held by MENA in 2015, government representatives highlighted some of the gaps confronting the scale-up of regional responses to climate change, resulting in 14 recommendations. These included prioritizing adaptation, supporting technology transfer, significantly increasing international climate financing, and enhancing institutional capacity across the region.

Efforts to implement such recommendations could be guided by a study by Babiker and Fehaid (2012) which presented an assessment of the mitigation potential in the region and the appropriate policy options to harness these opportunities. The study identified a significant potential for energy savings through elimination of inefficiencies and waste, and it found large mitigation opportunities in the residential and energy-intensive manufacturing sectors. The study also emphasized that policymakers should use both demand-side management and market-based policy instruments to take advantage of the enormous and cheap GHG emissions mitigation opportunities in MENA.

Least Developed Countries: The Crucial Role of Finance

Achala Abeysinghe, *Principal Researcher in the International Institute for Environment and Development (IIED); legal and strategic advisor to the Chair of the Least Developed Countries Group for the UNFCCC*

The lack of capacity and resources of the Least Developed Countries (LDCs) leaves them particularly vulnerable to climate change. Yet these countries are among the most committed and proactive on climate action, with continuous efforts to accelerate the transition to low-carbon, climate-resilient development.[1] Global solidarity and the support of the international community are critical for the achievement of crucial climate plans in LDCs.

All LDCs have submitted NDCs with commitments well exceeding their fair share of the global effort to combat climate change. They continue to develop ambitious strategies to take climate action and pursue sustainable development, including the LDC Renewable Energy and Energy Efficiency Initiative.[2] Gambia and Ethiopia are among the five countries rated by Climate Action Tracker as most ambitious in their NDCs. Overall, current LDC NDCs offer a considerable combined mitigation potential in their energy, forestry and land-use, agriculture and transport sectors.[3] Nearly all LDCs include an adaptation component in their NDCs, with the majority focusing on agriculture, water and forestry as their top priority sectors.

Despite the unquestionable determination of the LDCs to develop sustainably, mitigate GHG emissions, adapt to climate change, and address loss and damage, they lack the resources and tools to effectively implement their NDCs. Global support has lagged far behind what is required by LDCs, primarily due to a lack of climate finance. The adequacy, predictability and sustainability of global climate finance have become questionable.

The climate finance issue for LDCs is threefold. First, the promised $100 billion annually by 2020 in aid from developed countries is far from the amount actually needed for developing countries to implement their NDCs, and an agreed-upon roadmap to delivering even this promise is yet to be seen. So far, the Green Climate Fund has received pledges of $10.3 billion, and the dedicated LDC Fund remains practically empty, with a backlog of approved projects. Estimates suggest that $4 billion is still needed just for implementation of urgent and immediate adaptation needs recognized through National Adaptation Programs of Actions (NAPAs), which were produced by LDCs nearly a decade ago. Second, current and predicted global climate finance is negligible in comparison to what is required by LDCs. For example, the cost of LDCs implementing their NDCs alone is estimated to exceed $93 billion per year, including U.S. $53.8 billion for mitigation and $39.9 billion for adaptation costs (Rai *et al.*, 2015). Third, the climate finance that is available is not reaching those that need it most. Less than a third of available international public climate finance reaches the LDCs, with the majority instead channeled to upper and middle-income countries.

The delivery of the LDC's NDCs will not be possible unless and until the international community provides adequate, predictable and sustainable climate finance, and improves disbursement so that resources reach them. For LDCs it is particularly important that this funding comes from public sources and be grant-based, given the challenges they face attracting private investment. South-south cooperation also has an important role to play in maximizing limited resources.

Closing the climate finance gap to enable the implementation of LDCs' NDCs is crucial to achieving the long-term goals of the Paris Agreement and promoting the health and prosperity of the LDCs, enabling LDCs to develop sustainably without exacerbating the climate crisis.

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[1] LDC Group, Addis Ababa LDC Ministerial Communique. http://www.ldc-climate.org/media_briefings/media-briefing-ministers-from-least-developed-countries-commit-to-ambitious-climate-action-and-call-for-global-community-to-step-up-support-at-un-climate-change-negotiations/

[2] LDC Group, Renewable Energy and Energy Efficiency Initiative http://www.ldc-climate.org/press_release/least-developed-countries-launch-renewable-energy-and-energy-efficiency-initiative-join-global-partnership-to-rapidly-scale-up-clean-energy-transformation-worldwide/

[3] Synthesis of the LDC NDC analysis, Climate Analytics. http://climateanalytics.org/files/synthesis_of_the_ldcs____ndcs_analysis_impact_2017.10.04.pdf

Long Term Paris Goals

The long-term goal of international negotiations on climate change is stabilization of atmospheric concentrations of GHGs. This goal goes back to the United Nations Framework Convention on Climate Change that called for "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." Entering into force as of 21 March 1994, the UNFCCC set out clear principles on how to assess a time-frame for and level of stabilization but did not specify a specific target or path.

To operationalize this long-term goal required more input from the scientific community on the level and nature of climate change associated with different stabilization levels, and the ability of ecosystems, agriculture and the world's economies to adapt to such changes. The authors of succeeding reports of the Intergovernmental Panel on Climate Change—from the IPCC's Second Assessment Report through to the most recent Fifth Assessment Report (AR5), as well as various special reports—have, to a large extent, been charged to establish scientific foundations for targets and timetables needed to meet the overarching goal of the UNFCCC. Based on this growing set of information, the 21st UNFCCC Conference of the Parties (COP21) meeting in Paris in 2015 established more precise temperature targets by agreeing to the need to keep "aggregate emissions pathways consistent with holding the increase in global average temperature well below 2°C above preindustrial levels" and further adding the goal of "pursuing efforts to limit the temperature increase to 1.5°C."

Emissions Pathways Consistent with Goals

While the Paris Agreement focus on 2°C or possibly 1.5°C sets out specific temperature targets, there remain several issues in establishing emissions pathways consistent with these goals. Foremost among these are uncertainties in the Earth-system response to a specific emissions pathway. Then there is the question of what is meant by "well-below" 2°C. Finally, if we resolve those issues, there is the question of linking near-term targets with the long-term goal; doing more in the near term leaves more room in the future for hard-to-abate emissions, while betting on future zero or negative emissions technologies means more headroom in the near-term for countries to gradually transform energy, industry, agriculture and other sectors to zero-GHG technologies. We have also seen consideration of "overshoot" scenarios, where temperature and/or GHG concentrations rise above a level consistent with a long-term goal, but then fall back to that level in later years. These scenarios have been of particular interest in the case of the 1.5°C target because of the challenge of reducing emissions enough in the near-term to meet that goal.

To better understand the implications of these goals for emissions pathways, we have constructed various emissions pathways consistent with: (1) remaining below 2°C with a 50-50 chance, given our estimate of the uncertainty in climate response; (2) remaining below 2°C with a 2-in-3 chance; (3) remaining below 1.5°C with a 50-50 chance; and (4) a scenario that briefly overshoots 1.5°C but returns to that level by 2100. A general observation of much of the climate research community is that as a first approximation, temperature and GHG concentration increases over the century depend on cumulative emissions during that period. The specific time path of emissions—more now, less later; or less now, and more later—does not significantly change the long-term outcome. However, the time path can be important for policy design.

Our first set of simulations determines emissions paths consistent with staying below 2°C with a 50-50 chance (**Figure 36**). Included are two stabilization pathways, one

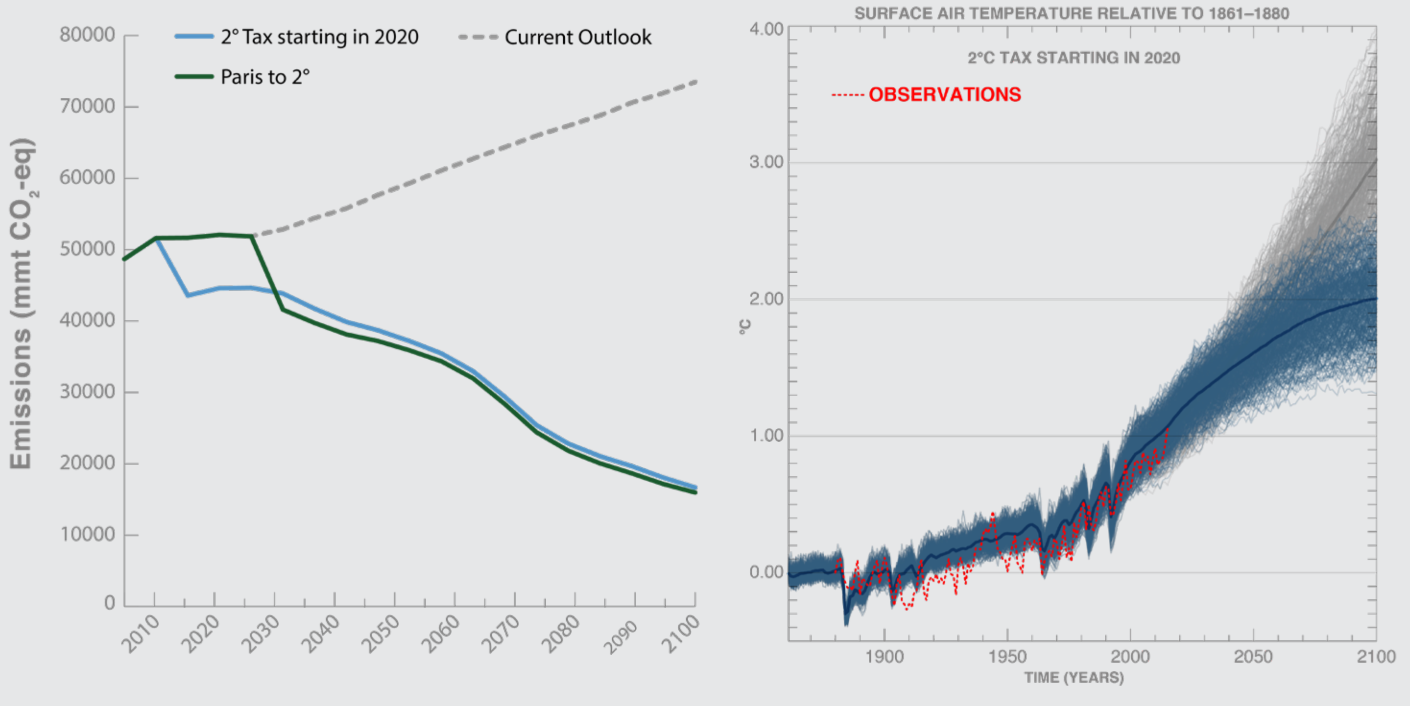

Figure 36. Emissions Pathways Consistent with 2°C with a 50-50 Chance

in which an optimal global carbon tax is implemented in 2020, the other in 2030, assuming that the NDCs from Paris have set the path through at least 2025. The needed initial tax, assumed to rise at 4% for the rest of the century, is $85 if started in 2020, or $122 if delayed until 2030 (in 2015 dollars). These taxes are superimposed against our Outlook scenario. These simulations suggest that the emissions path associated with the Paris NDCs is basically inconsistent with the 2°C target. It is certainly possible to achieve that target, but an economically optimal path (at least as technological options are defined within our modeling framework) would indicate that emissions should immediately fall, and then continue to decline. If we wait until 2030, the emissions need to be somewhat lower for the rest of the century—not much lower as there are 70 years to make up the difference—but it would then require an even sharper drop once the global policy is in place. The median temperature (dark blue line, right graph of Figure 36) peaks at 2°C by design. Given uncertainty in climate-system properties, the temperature rise could be, at the extremes, somewhat less than 1.5°C, or as much as 2.5°C. Staying below 2°C with only a 50-50 chance leaves open the chance of the temperature being well below 2°C or even 1.5°C, but this seems unlikely to be consistent with Paris Agreement language.

The IPCC has defined different degrees of likelihood—and their definition of "likely" is an outcome with greater than 66% probability, i.e. at least a ⅔ likelihood (or 2-in-3 chance). We have constructed emissions scenarios making it "likely" that the increase is less than 2°C (**Figure 37**). We superimpose these scenarios on the charts in Figure 36. These scenarios require an even greater emissions reduction starting immediately or in 2030, and a higher initial tax ($109 in 2020, $139 in 2030, in 2015 dollars). This results in a 50-50 chance of remaining below 1.8°C, and about a 25% chance of remaining below 1.5°C. However, there is still about a 1-in-3 chance of temperatures above 2°C, but essentially all trajectories remain below 2.5°C. These scenarios may be more consistent with the Paris language of "well below 2°C."

Aiming for 1.5°C with a 50-50 chance is a still more challenging task (**Figure 38**). Here we have shown two possible paths, one with an initial carbon price in 2020 of $130, rising at 4%, which keeps the median temperature below 1.5°C. The second, a scenario considering the difficulties of rapidly getting on the 1.5°C path, allows overshooting and then negative emissions technologies toward the end of the century.[6]

Finally, as we noted in passing, the emissions paths we calculate as "optimal" depend critically on our characterization of technology options and their costs. Our modeling system as used here does not include the possibility of massive reforestation or of negative emissions such as from biomass with carbon capture and storage (BECCS). The structure also leaves positive emissions in some sectors for which no reasonable cost abatement technologies can completely eliminate emissions. These include some emissions of methane from agriculture, nitrous oxide from fertilizers, and emissions from fossil use in energy-intensive industries. Our specification allows these to be reduced but not easily eliminated. That's why in Figure 36 and Figure 37, emissions remain positive through the end of the century.

To examine the implications of additional options for reducing or offsetting remaining emissions, we considered some very simple scenarios in which we assumed a significant forest sink or BECCS in the second half of the century, or that net emissions from all sources could go to zero post-2070 (**Figure 39**). These scenarios all generate climate outcomes consistent with 2°C with a 50-50 or "likely" chance as labeled, although we do not show the climate scenarios. They are generated on the basis that cumulative emissions remain the same as in the original scenarios in Figure 36 or Figure 37. Assuming this great emissions abatement potential in the second half of the century gives more headroom in the near term. While the quantities of BECCS and forest sinks are somewhat arbitrary, they are consistent with estimates of their potential in the IPCC and other literature. The net-zero emissions after 2070 is based directly on our

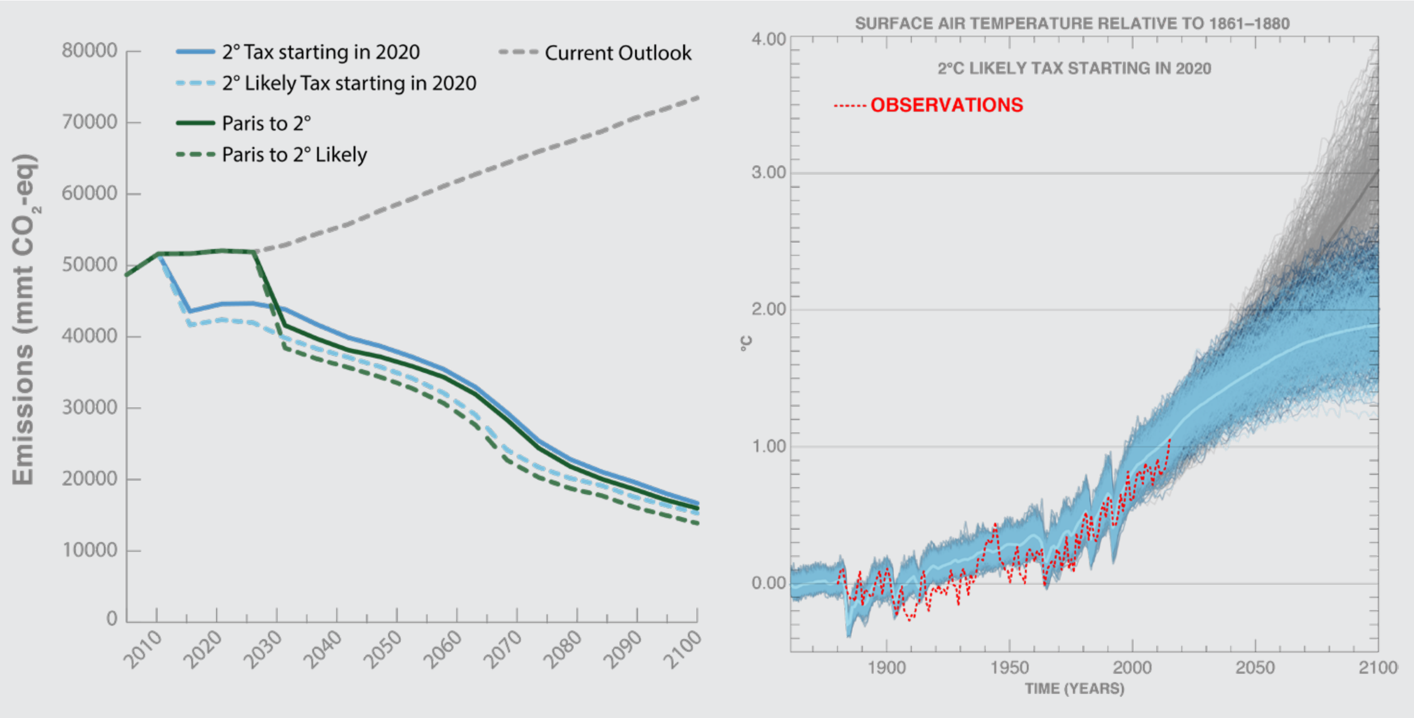

Figure 37. Emissions Scenarios "Likely" to Remain Below 2°C

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[6] Shell's Sky+Extra NBS scenario annual emissions (both with and without land-use change emissions). The corresponding temperature increase (1.5°C by 2100) is reported in the lowest curve on Figure 14 of Paltsev *et al.* (2018).

scenario, but arbitrarily we might consider reducing those emissions by other percentages, or assuming it goes to net-zero earlier. For the net-zero emissions scenario and the scenario with BECCS, for a 50-50 chance of achieving the target of 2°C, emissions do not need to drop rapidly immediately.

If these are real possibilities, then our current path does not look that far out of line with a 50-50 chance of achieving the target of 2°C. But if we need to achieve the "likely" 2°C target, immediate reductions are needed, though not as drastic as in the absence of these options. We have not combined these future options; that would obviously lead to more headroom. Achieving any one of these targets at the level we have assumed would be a big stretch in our judgement. Achieving all three jointly even more so, because it would be even more difficult to use BECCS if at the same time, land is permanently reforested for carbon sequestration.

The overall point of this exercise is to emphasize that the 'consistency' of the current path with a particular carbon target depends importantly on what you assume about potential abatement opportunities in the latter part of the century. While betting on such opportunities would relax near-term abatement requirements, it would also open up a greater risk of not meeting those targets if those abatement opportunities do not come to pass.

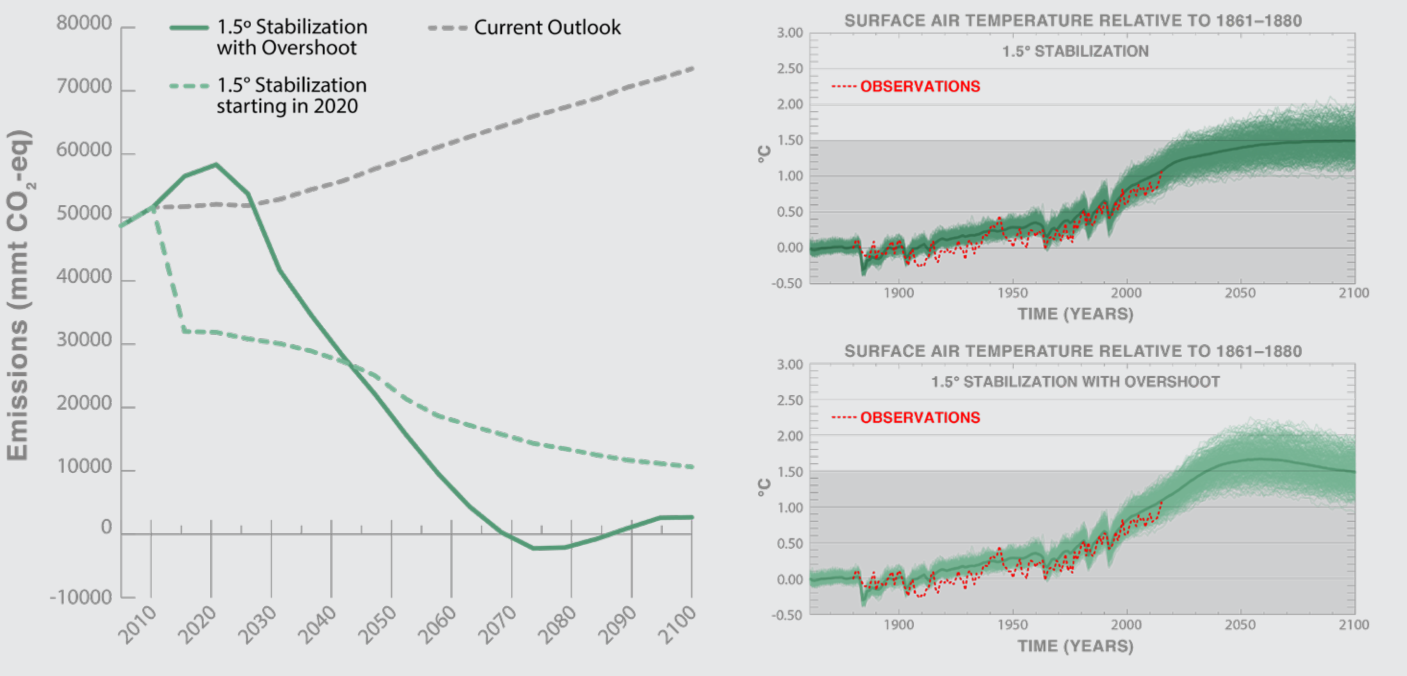

Figure 38. Emissions scenarios and 1.5°C

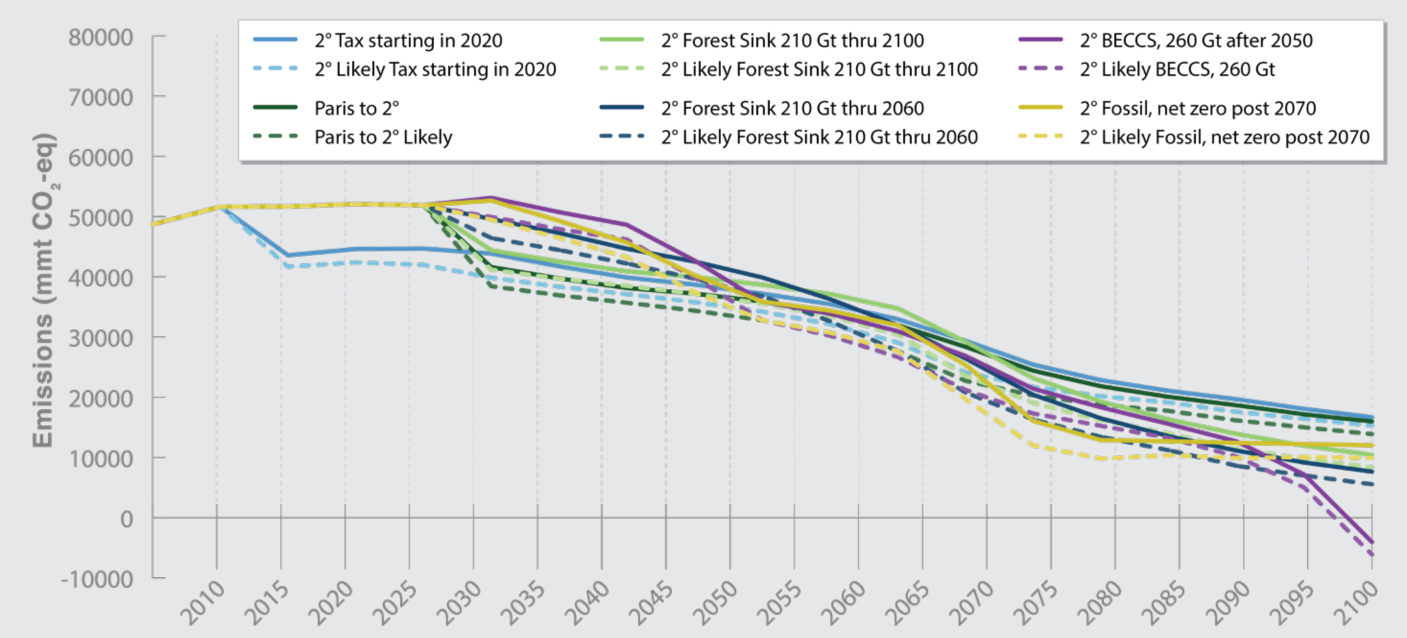

Figure 39. Emissions Paths with More Abatement Opportunities in the second Half of the Century.

Preparing for Tomorrow Today

The world's aggressive long-term goals of keeping the average global surface temperature rise well below 2 degrees Celsius or even below 1.5 degrees from the preindustrial level is in keeping with the risks posed by climate change. It remains challenging to predict in precise ways how climate will change at all levels from local to regional to global, and what those changes would mean for the natural resources on which we depend. As we continue to run the experiment of what increasing greenhouses gases means for the Earth, we are seeing that in a broad sense the climate is doing what our models have been telling us for some decades now—it is warmer, with more extremes, and more moisture in the atmosphere.

While it is difficult to be precise—different scientists have advanced different perspectives on what climate change would look like—overall, having worked on this issue for decades now, it appears that the climate is changing faster and the details of those changes are more severe than we had projected. Arctic ocean ice is disappearing faster, Greenland and Antarctic ice sheets are melting faster; heavy precipitation events are becoming more severe sooner; tropical cyclones are intensifying and slowing down, creating much larger precipitation events and more severe flooding; and extreme heat is having serious effects on people and crops. In most of these cases, while we may not have predicted the severity of the changes coming this soon, what we have now observed is consistent with how we expect the Earth system to respond.

To fully understand exactly how the system will respond to ever-increasing greenhouse gases, we would likely need to continue running the experiment. However, that would be foolhardy; while we cannot see precisely what is ahead, if we continue on this path, we can see well enough to know that it poses severe risks. Failing to stop and stabilize at some level is not a viable option—the Earth would become largely uninhabitable, unable to support a population of 7-plus, much less 10, billion people. Clearly we need to reverse course, reducing greenhouse gas emissions instead of allowing them to increase.

While the long-term goals of the Paris Agreement would seem to suggest that our world leaders have taken these risks seriously, the near-term targets in the accord are largely not on track to meet those long-term goals without an abrupt change in direction soon—unless we can count on technology saving us sometime in the second half of the century by delivering affordable negative-emissions technology, or getting to zero emissions everywhere in the economy through some mix of innovations. This would need to include crop production without nitrous oxide emissions, rice and ruminants without methane (or dropping those from our diets), and metals and cement production without emissions or building without them. More aggressive action sooner rather than later on mitigation will give us a better chance of meeting the long-term targets. At the same time, we need to prepare our homes, communities and the industries on which we depend for the climate change we will experience, even if we manage to hold the increase to less than 2 or 1.5 degrees, and make even greater preparations to account for the risk that we may fail to hold the line on the temperature rise.

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Appendix

This appendix contains projections for global economic growth, energy use, emissions and other variables to 2050. Similar tables for 18 regions of the world are available at http://globalchange.mit.edu/Outlook2018

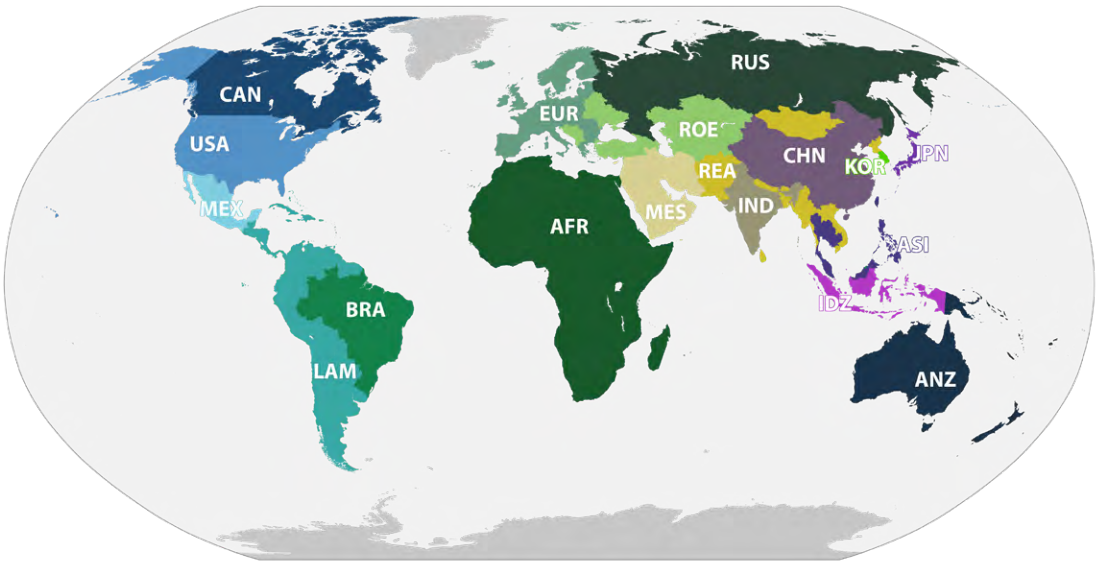
MIT Joint Program Food, Water, Energy & Climate Outlook 2018 **Projection Data Tables**

	Region: World	Units	2015	2020	2025	2030	2035	2040	2045	2050
Economic Indicators	GDP	bil 2015 $	75233.5	86293.3	98924.3	113343.5	129196.8	146580.3	165349.7	185799.1
	Consumption	bil 2015 $	44956.2	51650.3	59239.1	68113.6	77636.3	87962.3	98916.2	110823.2
	GDP growth	% / yr	2.8	2.8	2.8	2.7	2.6	2.4	2.4	2.3
	Population	millions	7383.0	7795.5	8185.6	8551.2	8892.7	9210.3	9504.2	9771.8
	GDP *per capita*	2015 $	10190.1	11069.7	12085.1	13254.7	14528.4	15914.8	17397.5	19013.8
GHG Emissions	CO_2 – fossil	Mt CO_2	33109.7	33327.0	33525.8	33809.9	34825.6	35802.7	36936.2	37963.4
	CO_2 – industrial	Mt CO_2	2995.1	3106.4	3084.7	2647.1	2486.4	2488.5	2409.6	2465.0
	CH_4	Mt	405.7	353.6	364.7	364.6	378.3	401.3	414.8	430.0
	N_2O	Mt	12.4	12.2	12.8	12.0	12.3	12.8	13.0	13.0
	PFCs	kt CF_4	11.8	7.2	7.0	6.1	6.3	6.5	6.6	6.9
	SF_6	kt	6.0	3.7	3.2	2.9	2.8	2.6	2.3	2.5
	HFCs	kt HFC-134a	355.6	216.0	202.3	200.2	229.9	266.8	303.2	339.6
	Total GHG net of Land Use	Mt CO_2e	51430.0	49978.8	50601.6	50223.1	51559.2	53371.6	54896.6	56464.8
	CO_2 – land use change	*Mt CO_2*	*562.8*	*1611.8*	*1236.5*	*1108.5*	*758.1*	*497.8*	*365.5*	*277.6*
Primary Energy Use	Coal	EJ	160.6	155.9	153.2	153.7	155.3	155.0	157.3	158.6
	Oil	EJ	181.2	192.1	198.1	202.6	209.8	217.7	226.7	237.3
	Biofuels	EJ	13.9	17.6	19.6	22.4	22.8	23.7	22.7	22.3
	Gas	EJ	123.0	125.5	130.8	135.9	145.8	156.9	166.5	174.5
	Nuclear	EJ	26.0	27.6	27.6	28.5	27.3	26.2	23.5	23.5
	Hydro	EJ	38.4	38.9	39.4	40.0	40.5	41.0	41.5	42.1
	Renewables	EJ	11.1	19.8	29.9	40.1	51.5	63.6	68.0	72.1
Electricity Production	Coal	TWh	9780.6	9774.1	9664.1	9408.9	9703.9	9751.2	10429.5	10943.4
	Oil	TWh	990.4	888.3	656.8	517.6	429.6	328.4	237.9	176.5
	Gas	TWh	5125.9	5389.5	6053.4	7121.3	7882.1	8942.0	10024.9	10839.0
	Nuclear	TWh	2538.7	2749.2	2801.4	2931.6	2836.6	2718.0	2436.2	2456.3
	Hydro	TWh	3755.9	3858.1	3963.3	4071.5	4182.9	4297.5	4415.7	4537.2
	Renewables	TWh	1169.7	2114.2	3242.9	4406.6	5728.1	7174.7	7781.0	8378.6
	Bioenergy	TWh	586.4	727.0	900.0	1010.3	1146.1	1330.7	1412.3	1490.2
Household Transportation	Number of vehicles	millions	1111.7	1234.5	1317.4	1384.7	1472.5	1568.4	1674.6	1789.1
	Vehicle miles traveled	trillions	1.4	1.8	2.2	2.5	2.8	3.1	3.5	3.8
	Miles per gallon	mpg	23.2	24.2	25.7	27.6	29.3	30.6	31.4	31.7
	Vehicles per person		*0.15*	*0.16*	*0.16*	*0.16*	*0.17*	*0.17*	*0.18*	*0.18*
Land Use	Cropland	Mha	1527.4	1549.9	1549.0	1553.4	1551.9	1559.4	1565.0	1572.2
	Biofuels	Mha	32.4	40.4	52.1	63.7	72.5	78.4	80.8	80.9
	Pasture	Mha	1895.6	1957.3	1987.7	2020.8	2042.8	2047.4	2051.5	2053.4
	Managed forest	Mha	750.6	752.6	752.4	761.4	768.5	774.4	777.0	777.1
	Natural grassland	Mha	1423.2	1344.3	1318.1	1274.8	1249.8	1234.7	1226.9	1223.1
	Natural forest	Mha	3277.6	3262.4	3247.6	3232.8	3221.3	3212.6	3205.7	3200.2
	Other	Mha	4015.0	4015.0	4015.0	4015.0	4015.0	4015.0	4015.0	4015.0
	Total land area	Mha	12921.9	12921.9	12921.9	12921.9	12921.9	12921.9	12921.9	12921.9
Air Pollutant Emissions	SO_2	Tg	104.1	96.9	89.0	83.5	79.9	75.8	71.1	68.3
	NO_x	Tg	136.7	137.0	141.5	146.7	154.1	165.3	169.6	175.7
	Ammonia	Tg	57.1	56.8	58.5	57.6	57.7	59.2	58.6	58.2
	Volatile organic compounds	Tg	164.8	131.7	136.6	141.0	146.4	157.4	160.4	164.3
	Black carbon	Tg	5.3	4.8	5.0	5.0	5.0	5.2	5.1	4.9
	Organic particulates	Tg	16.4	14.9	15.4	15.6	15.5	16.5	15.9	15.5
	Carbon monoxide	Tg	1159.9	717.9	790.3	844.9	887.7	1001.4	1016.4	1035.0
Agricultural & food outputs	Crop	bil 2015 $	2639.1	2925.5	3204.4	3373.4	3648.1	3962.4	4260.8	4631.1
	Livestock	bil 2015 $	1851.0	2129.9	2457.7	2741.4	3044.1	3379.6	3732.5	4123.8
	Food	bil 2015 $	6751.1	7744.8	8860.1	10130.6	11388.8	12712.4	14107.3	15586.1
Agricultural & food prices (2015 price = 1)	Crop		1.00	1.07	1.07	1.13	1.17	1.22	1.27	1.33
	Livestock		1.00	1.13	1.24	1.39	1.51	1.66	1.81	1.96
	Food		1.00	1.03	1.02	1.03	1.03	1.03	1.04	1.04
Energy prices (2015 price = 1)	Coal		1.00	0.96	0.92	0.92	0.90	0.89	0.90	0.91
	Oil		1.00	1.06	1.07	1.05	1.05	1.06	1.07	1.09
	Gas		1.00	1.02	1.02	1.00	1.01	1.03	1.04	1.04
	Electricity		1.00	1.11	1.20	1.27	1.29	1.31	1.31	1.31

IGSM regions:

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

Regional data tables available at: http://globalchange.mit.edu/Outlook2018



Country	Region
Afghanistan	REA
Albania	ROE
Algeria	AFR
American Samoa	ANZ
Andorra	ROE
Angola	AFR
Anguilla	LAM
Antigua & Barbuda	LAM
Argentina	LAM
Armenia	ROE
Aruba	LAM
Australia	ANZ
Austria	EUR
Azerbaijan	ROE
Bahamas	LAM
Bahrain	MES
Bangladesh	REA
Barbados	LAM
Belarus	ROE
Belgium	EUR
Belize	LAM
Benin	AFR
Bermuda	LAM
Bhutan	REA
Bolivia	LAM
Bosnia and Herzegovina	ROE
Botswana	AFR
Brazil	BRA
Brunei	REA
Bulgaria	EUR
Burkina Faso	AFR
Burundi	AFR
Cambodia	REA
Cameroon	AFR
Canada	CAN
Cape Verde	AFR
Cayman Islands	LAM
Central African Republic	AFR
Chad	AFR
Chile	LAM
China	CHN
Côte d'Ivoire	AFR
Colombia	LAM
Comoros	AFR
Congo	AFR
Congo, Dem. Rep. (Zaire)	AFR
Cook Islands	ANZ
Costa Rica	LAM
Croatia	ROE
Cuba	LAM
Cyprus	EUR
Czech Republic	EUR
Denmark	EUR
Djibouti	AFR
Dominica	LAM
Dominican Republic	LAM
Ecuador	LAM
Egypt	AFR
El Salvador	LAM
Equatorial Guinea	AFR
Eritrea	AFR
Estonia	EUR
Ethiopia	AFR
Falkland Islands	LAM
Faroe Islands	ROE
Fiji	ANZ
Finland	EUR
France	EUR
French Guiana	LAM
French Polynesia	ANZ
Gabon	AFR
Gambia	AFR
Georgia	ROE
Germany	EUR
Ghana	AFR
Gibraltar	ROE
Greece	EUR
Greenland	LAM
Grenada	LAM
Guadeloupe	LAM
Guam	ANZ
Guatemala	LAM
Guinea	AFR
Guinea-Bissau	AFR
Guyana	LAM
Haiti	LAM
Honduras	LAM
Hong Kong	CHN
Hungary	EUR
Iceland	EUR
India	IND
Indonesia	IDZ
Iran	MES
Iraq	MES
Ireland	EUR
Israel	MES
Italy	EUR
Jamaica	LAM
Japan	JPN
Jordan	MES
Kazakhstan	ROE
Kenya	AFR
Kiribati	ANZ
Korea	KOR
Korea, Dem. Ppl. Rep.	REA
Kuwait	MES
Kyrgyzstan	ROE
Laos	REA
Latvia	EUR
Lebanon	MES
Lesotho	AFR
Liberia	AFR
Liechtenstein	EUR
Lithuania	EUR
Luxembourg	EUR
Libya	AFR
Macau	REA
Macedonia	ROE
Madagascar	AFR
Malawi	AFR
Malaysia	ASI
Maldives	REA
Mali	AFR
Malta	EUR
Marshall Islands	ANZ
Martinique	LAM
Mauritania	AFR
Mauritius	AFR
Mayotte	AFR
Mexico	MEX
Micronesia	ANZ
Moldova	ROE
Monaco	ROE
Mongolia	REA
Montserrat	LAM
Morocco	AFR
Mozambique	AFR
Myanmar	REA
Namibia	AFR
Nauru	ANZ
Nepal	REA
Netherlands	EUR
Netherlands Antilles	LAM
New Caledonia	ANZ
New Zealand	ANZ
Nicaragua	LAM
Niger	AFR
Nigeria	AFR
Niue	ANZ
Norfolk Islands	ANZ
Northern Mariana Islands	ANZ
Norway	EUR
Oman	MES
Pakistan	REA
Palestine	MES
Panama	LAM
Papua New Guinea	ANZ
Paraguay	LAM
Peru	LAM
Philippines	ASI
Poland	EUR
Portugal	EUR
Puerto Rico	LAM
Qatar	MES
Réunion	AFR
Romania	EUR
Russian Federation	RUS
Rwanda	AFR
Saint Helena	AFR
Saint Kitts and Nevis	LAM
Saint Lucia	LAM
Saint Pierre & Miquelon	LAM
Saint Vincent & Grenadines	LAM
Samoa	ANZ
San Marino	ROE
São Tomé and Príncipe	AFR
Saudi Arabia	MES
Senegal	AFR
Serbia and Montenegro	ROE
Seychelles	AFR
Sierra Leone	AFR
Singapore	ASI
Slovakia	EUR
Slovenia	EUR
Solomon Islands	ANZ
Somalia	AFR
South African Republic	AFR
Spain	EUR
Sri Lanka	REA
Sudan	AFR
Suriname	LAM
Swaziland	AFR
Sweden	EUR
Switzerland	EUR
Syria	MES
Taiwan	ASI
Tajikistan	ROE
Tanzania	AFR
Thailand	ASI
Timor-Leste	REA
Togo	AFR
Tokelau	ANZ
Tonga	ANZ
Trinidad and Tobago	LAM
Tunisia	AFR
Turkey	ROE
Turkmenistan	ROE
Turks and Caicos Islands	LAM
Tuvalu	ANZ
Uganda	AFR
Ukraine	ROE
United Arab Emirates	MES
United Kingdom	EUR
United States	USA
Uruguay	LAM
Uzbekistan	ROE
Vanuatu	ANZ
Venezuela	LAM
Vietnam	REA
Virgin Islands, British	LAM
Virgin Islands, U.S.	LAM
Wallis and Futuna	ANZ
Yemen	MES
Zambia	AFR
Zimbabwe	AFR

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