MIT JOINT PROGRAM ON THE SCIENCE AND POLICY OF GLOBAL CHANGE

FOOD • WATER • ENERGY • CLIMATE OUTLOOK

PERSPECTIVES FROM 2016

AUTHORS Henry Chen • Qudsia Ejaz • Xiang Gao • Jin Huang • Jennifer Morris • Erwan Monier • Sergey Paltsev • John Reilly • Adam Schlosser • Jeffery Scott • Andrei Sokolov

CONTRIBUTORS Patrick Brown, Howard Herzog, Frank O'Sullivan, Nidhi Santen & Apurba Sakti, **MIT Energy Initiative** • James Primrose, **BP** • Irfan Ali & Samuel Thernstrom, **Energy Innovation Reform Project** • Élodie Blanc, Kenneth Strzepek & Niven Winchester, **MIT Joint Program**

DESIGN & EDITING Jamie Bartholomay • Mark Dwortzan • Jennifer Morris • Anne Slinn

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.*

2016 Outlook: Exploring Global Changes

The ***2016 Food, Water, Energy and Climate Outlook*** continues a process, started in 2012 by the MIT Joint Program, of providing an annual 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.

This year we expand the Outlook to report on projected effects of climate change and other factors on crop yields and water resources, and challenges for global food and water availability. In addition, we examine the goal of stabilizing concentrations of greenhouse gases at levels consistent with targets identified in international negotiations. Achieving stabilization of concentrations at reasonable cost will most likely require significant advances in key technologies. For this year's Outlook, we have invited guest contributors to offer perspectives on barriers to commercializing key energy technologies and systems, and the technological breakthroughs needed to make them technically and economically viable—as well as on major food and water challenges.

CONTENTS

About the 2016 Outlook

For this year's Outlook, we have left unchanged our central forecast of energy, land use and climate, but added new projections of the possible implications of these changes for major crop yields in breadbasket regions of the world and for global and regional water resources. Last year's Outlook provided early estimates of the outcome of the Paris climate negotiations (COP21) for energy and land use, and its implications for climate—projections which, though published prior to the conclusion of COP21, captured the broad outline of what was ultimately agreed upon in Paris.

While several countries made late commitments that were not fully incorporated in the 2015 Outlook, many of these pledges, whether targeting a percentage reduction in emissions below a forecasted baseline or a reduction in emissions intensity, appear to be little more than business-as-usual. There also remains considerable guesswork in interpreting commitments, which are often defined broadly and do not indicate specific policies and measures countries will employ to implement them. For this level of detail, which will be necessary for making meaningful projections, many are looking to COP23, slated for November 2017 in Asia. We thus decided to leave our main energy and climate projections unchanged rather than engage in further speculation of how or whether commitments will be implemented, and continue to use our 2015 *COP21 Outlook* scenario in this year's Outlook.

In our expanded focus on food and water, we provide projections of yields of major crops in breadbasket regions of the world and impacts on global and regional water resources. These projections are based on the climate scenarios from our central emissions scenario that is unchanged from the 2015 Outlook. Along with a new section on energy technology challenges and opportunities posed by the need to stabilize the climate, we include perspectives on food and water challenges the world faces that climate change may aggravate or, in some cases or regions, relieve.

Because international negotiations have reiterated the goal of stabilizing climate at a level of 2°C or less warming from preindustrial levels, we have added scenarios that address this goal. These help us to better understand the challenge we face in getting from where the world is heading to where it aspires to end up. An important uncertainty in whether a given emissions path will remain below 2°C is in the Earth-system response to a given forcing. To illustrate this, we develop three scenarios consistent with stabilization at 2°C—median, low (5th percentile) and high (95th percentile) climate sensitivity. These alternatives represent uncertainty in climate response to greenhouse gas (GHG) forcing, and are approximate bounds on emissions paths needed to stay below 2°C. As in the 2015 Outlook, we also adjust ocean heat uptake and aerosol forcing to ensure that simulations match the historical climate record. Another way of looking at these scenarios is that for the median, low and high climate response, we would have approximately a 50%, 34% and 66% chance, respectively, of staying below 2°C.

There are three key aspects of the climate change issue that indicate much of our climate future for the next few decades has already been determined:

- The long-term accumulation of GHGs with long lifetimes;
- A climate system with inertia so that it takes decades to millennia, as in the case of sea level, to see the full effect of current concentrations; and
- The added inertia in the energy system due to long-lived capital investments and institutions that can be slow to change.

While we need to continue to reduce emissions, much of what will happen depends on how uncertainties about the climate response resolve themselves.

A major debate in the literature has been whether the climate goal can be met with existing technology or whether we need revolutionary new technology. From an economic perspective, it is not a ques-

tion of whether we can do it, but at what cost. We clearly have very low- and virtually zero-carbon options such as nuclear, solar, wind and hydropower, and we can turn electricity into heat to replace fossil fuels in end use. Vehicles could be electric-powered or run on sustainably grown biofuels. Cities could be reconfigured to use mostly mass transport, bicycles and walking. We could reforest or adopt agricultural practices that take carbon from the atmosphere.

While we could pursue these options and reach very low GHG emissions, all indications are that scaling up these technologies and practices as they now exist would entail significant costs or public acceptance challenges. Even though many of these technologies have been commercialized in some locations and at some scale, they pose other risks (nuclear safety), face resource limits (hydro) or intermittency issues (solar, wind power), offer difficult trade-offs (food or fuel) or involve significant lifestyle changes (alternative commuting options).

Thus we have reached out to experts in the MIT Joint Program, MIT Energy Initiative and Energy Information Reform Project to describe barriers to commercializing key energy technologies and systems, along with the hoped-for technological breakthroughs that could make them technically and economically viable. A reasonable goal of technological advance is to provide the energy services people want at an affordable cost without forcing significant changes in how they go about their daily lives. While not meant to encompass all possible mitigation avenues, the areas we focus on in this Outlook—nuclear, biomass energy, solar electricity, energy storage, the electric grid and carbon capture and storage—are among the top areas for energy supply where innovation could facilitate the move toward a lower carbon future.

Our economic model includes normal improvements in labor productivity that affect all technologies, but, except for specific scenarios, we do not include major new breakthroughs in energy technologies that could make mitigation much more affordable. In the Energy Technology Paths and Research Challenges section of this report, contributed perspectives on potential advances in key technologies offer ideas of how each may improve. With significant gains in one or another of these technologies, the energy mix we project in our stabilization scenarios could change substantially. By assuming different mixes of costs, we portray scenarios where one or another of these advanced technologies plays a dominant role. These scenarios are illustrative, and we have not clearly tied specific scenarios to specific advances described in the contributed perspectives. The technology-cost ranges used are within those estimated by the International Energy Agency (IEA/NEA, 2015).

Detailed regional projections for economic, energy, emissions, land use, ocean acidity, precipitation and temperature change from our 2015 Outlook remain available in tabular form and in the previous Outlook. Results are summarized for three country groups: *Developed* countries (U.S., Canada, Europe, Japan, Australia and New Zealand); an approximation of *Other G20* nations (China, India, Russia, Brazil, Mexico and several fast-growing Asian economies); and the *Rest of the World*. Online tables are available for each of the individual regions of our Economic Projection and Policy Analysis (EPPA) Model (see **Box 1** for regional classification details).

For energy and emissions projections consistent with stabilization below 2°C, we report data only at the global level. Regional projections depend crucially on how these policies would be implemented, which regions would participate and what each would commit to do—all of which remain highly speculative. To produce these scenarios, we assume a globally uniform, rising carbon price that keeps cumulative emissions below a level consistent with 2°C. We stay with the COP21 commitments through 2025, and then go immediately to a globally efficient carbon-pricing strategy consistent with staying below 2°C. While this rapid transition is unlikely to be politically realistic, it is not clear there is a path from 2025 onward that remains below 2°C that does not require extraordinary political agreement or sudden and unforeseen breakthroughs in technology.

Please note that all units of measurement are based on the metric system.

Box 1.

Regional Classification Details

The IGSM modeling system used to generate the projections in this Outlook divides the global economy into 16 regions (Figure 1). These regions do not align exactly with the G20, the 20 largest economies of the world. The group we identify as the *Other G20* includes the Dynamic Asia region. It is comprised of Indonesia and South Korea (both G20 members), as well as Malaysia, Philippines, Singapore, Taiwan and Thailand that are not among the G20. Conversely, South Africa, Argentina, Saudi Arabia and Turkey are G20 countries, but are part of other regions in our model, and are included in the *Rest of the World* grouping. EUR is the EU-27, plus Norway, Switzerland, Iceland and Liechtenstein.

A full list of the countries included in each IGSM region is provided in the Appendix and supplementary projection tables available online at http://globalchange.mit.edu/Outlook2016.

For the reporting in this Outlook, the regions are further aggregated into 3 broad groups: *Developed*, *Other G20*, and *Rest of the World*.

AFR	Africa
ANZ	Australia & New Zealand
ASI	Dynamic Asia
BRA	Brazil
CAN	Canada
CHN	China
EUR	Europe/EU+
IND	India

JPN	Japan
LAM	Other Latin America
MES	Middle East
MEX	Mexico
REA	Other East Asia
ROE	Other Europe & Central Asia
RUS	Russia
USA	United States

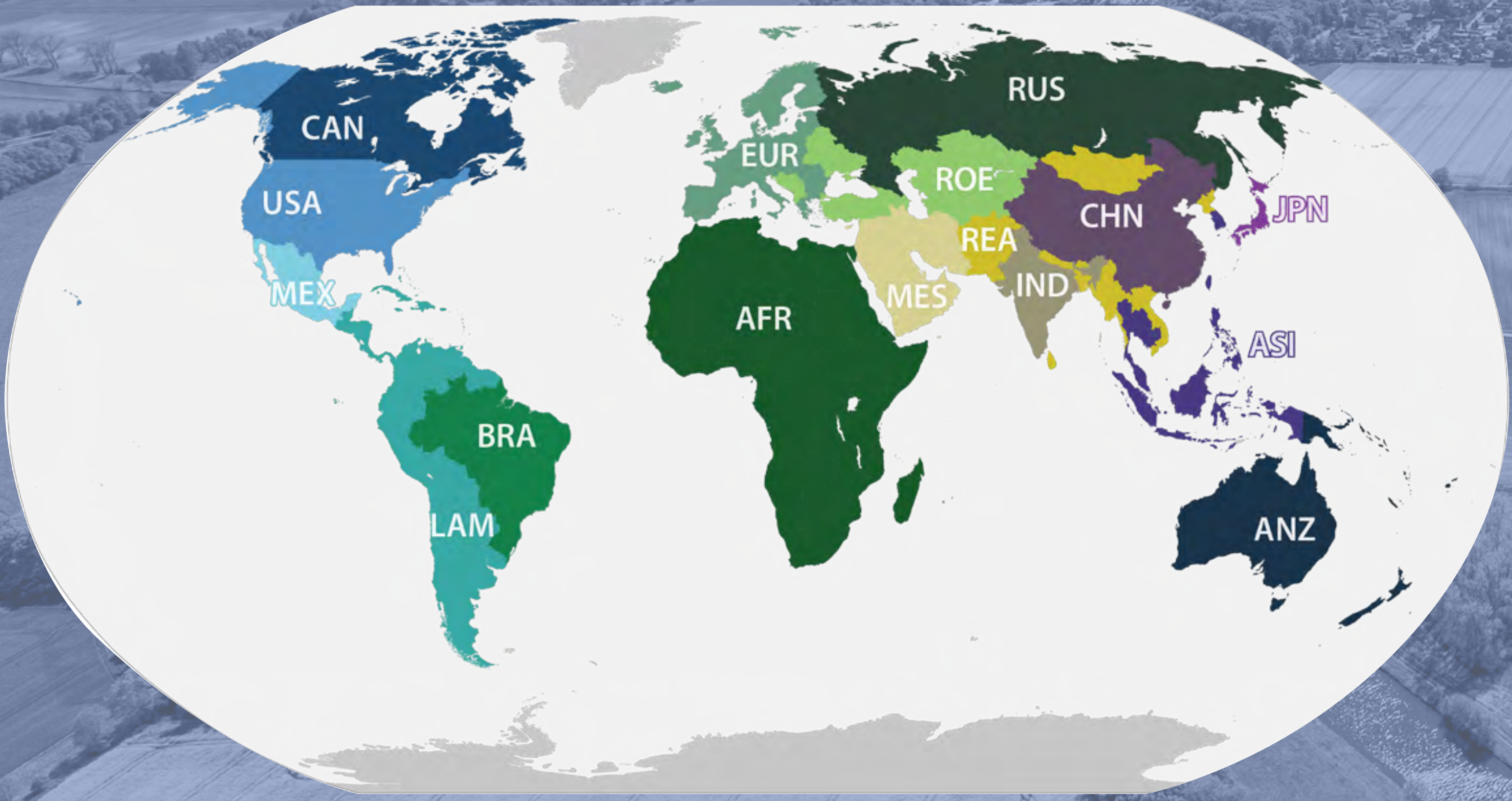


Figure 1. IGSM regions

Key Findings

COP21 Implications

Energy, Emissions & Climate

As detailed in the 2015 Outlook, on the assumption that Paris pledges are met and retained in the post-2030 period, future emissions growth will come from the *Other G20* and developing countries, accelerating changes in global and regional temperatures, precipitation, land use, sea-level rise and ocean acidification.

- Global emissions rise to 64 gigatons (Gt) carbon dioxide-equivalent (CO_2-eq) emissions by 2050 and 78 Gt by 2100 (a 63% increase in emissions relative to 2010). By 2050, the *Developed* countries account for about 15% of global emissions.
- Energy from fossil fuels continues to account for about 75% of global primary energy by 2050, despite rapid growth in renewables and nuclear, in part due to natural gas.
- The global mean surface temperature increase is in the range of 1.9 to 2.6°C (central estimate 2.2°C) by 2050 relative to the preindustrial level (1860–1880 mean), and 3.1 to 5.2°C (central estimate 3.7°C) by 2100.
- The global mean precipitation increase ranges from 3.9 to 5.3% by 2050 relative to the preindustrial level, and 7.1 to 11.4% (central estimate 7.9%) by 2100.
- Thermal expansion and land glacier melting contribute 0.15 to 0.23 meters to sea-level rise from the preindustrial level by 2050, and 0.3 to 0.48 meters (central estimate 0.35 meters) by 2100.

Agriculture

- The models we have developed that emulate major globally gridded crop models (GGCMs) project, for the most part, positive impacts on crop yields through the end of the century in the breadbasket regions considered. By the end of the century, projected yields increase from between 0.02 tons per hectare (t/Ha) to 0.75 t/Ha for maize in the U.S., 0.03 t/Ha to 0.9 t/Ha for upland rice in Southeast Asia, –0.07 t/Ha to 0.74 t/Ha for soybean in Brazil, and 0.1 t/Ha to 0.8 t/Ha for wheat in Europe, depending on the climate change scenario and crop model.
- In published work, the crop model emulators match closely the actual GGCM they were developed to emulate. The projections of current yields (circa 2015) vary greatly among models and do not replicate actual yields for these crops in the regions simulated. There are also large differences in the response to climate change, making the choice of crop model emulator a much larger source of differences in projections than the simulated climate scenarios.
- For maize in the U.S. and wheat in Europe, we find larger increases in yields in the north than in the south of the breadbasket areas. We would expect production of these crops to shift northward under these conditions.
- For soybean and upland rice, the divergence of impact among crop model emulators is larger, so conclusions are less clear, but an overall beneficial effect of climate change on upland rice is projected in Southern China.
- A large share of the beneficial impact of climate change is attributed to increases in CO_2 concentrations, which improve crop water-use efficiency and crop productivity. When not accounting for CO_2 effects, crop yields are reduced by between 8% for maize and 33% for rice. There remains a wide range of estimates of the so-called CO_2 fertilization effect, and evidence that while yields may increase, the quality of cereals, in terms of proteins and other nutrients, may be reduced.
- While climate change may advantage some areas, extreme heat and drought linked to a changing climate are likely to increase the frequency of major crop failures. And the strong gradient of yield changes across breadbasket regions as projected by some of the model emulators could create dislocation and relocation adjustment costs.

Water

- The water stress index (WSI), a measure developed by water-resource experts, shows increases in water stress in most regions, resulting from increasing demand due to population and economic activity, as well as from changes in climate.
- In many developing countries where populations are growing and economic activity is expanding, demand growth is a bigger source of increasing water stress than changes in climate, but in many regions climate change exacerbates that stress.
- Water demand growth is less of a factor in developed regions, where it has slowed or peaked.
- In some basins, increased water stress is mainly driven by irrigation demand and other water withdrawals, while in others the primary cause is decreased runoff due to decreased precipitation. In certain basins, increased precipitation and runoff are enough to compensate for increased water demand.
- The largest relative increase in the WSI is found in Africa, largely driven by increases in population and economic output.
- Approximately 1.5 billion additional people will experience stressed water conditions worldwide by 2050, of which approximately one billion will experience heavily to extremely stressed water conditions.
- Uncertainty in the climate change pattern plays a role in both where people will face water stress and what level of water stress they will face.

Meeting 2°C and Energy Technologies

- By our estimate, the emissions path under COP21 will result in atmospheric greenhouse gas levels that far exceed those consistent with the 2°C goal. How much we need to do immediately depends on the availability of low-cost, low-carbon options in the future.
- If nothing beyond the COP21 proposals is implemented, then by 2030 the world will be within about five years of hitting the cumulative emissions level that the IPCC Working Group I estimates as consistent with there being a 50% chance of holding the temperature increase to less than 2°C. With high climate sensitivity, the 2°C target may be exceeded in as little as 15 to 20 years from now. Even with low climate sensitivity, on this path, the 2°C target will be passed shortly after midcentury.
- Meeting 2°C requires drastic changes in the global energy mix. Depending on the relative costs of technologies, different technologies could dominate in order to meet a 2°C target.
- Depending on technological advances, the regulatory environment and public acceptance, a variety of different energy technologies could play a dominant role. The world could rely heavily on nuclear, renewables, biomass or carbon capture and storage (CCS), or some combination thereof. While one or more may turn out not to be important because expected breakthroughs do not occur, a portfolio of research and development is needed because we cannot predict which of these and other technologies may prove most successful.

Box 2 summarizes the major updates and changes in the 2016 Outlook. The remaining report describes the details behind these broad conclusions.

Box 2.

New in the 2016 Outlook

Emissions & Energy Scenarios for Stabilization

Scenarios consistent with keeping the global temperature rise below 2°C are included, and compared with the 2015 *COP21 Outlook* scenario.

Water Resources

Impacts of COP21 climate projections on global water resources are simulated, using our Water Resource System (WRS).

Contributed Perspective on Food and Water Challenges

Climate will affect food and water availability, but broader issues of economic development, population growth and other factors may be equally important. Understanding these broader issues is important in determining how the world can cope with the additional challenge of climate.

Crop Yields

Impacts of COP21 climate projections on major crop yields (corn, wheat, upland rice and soybean) in major "breadbasket" regions of the world are simulated, using statistical models trained to emulate the results of major globally gridded crop models. These simulations illustrate general trends and structural uncertainty in estimates stemming from different modeling approaches.

Contributed Perspective on Energy Technologies

Discussions of barriers and hoped-for breakthroughs in major energy technologies including nuclear, biomass energy, solar electricity, electricity storage, the electricity grid and carbon capture and storage.

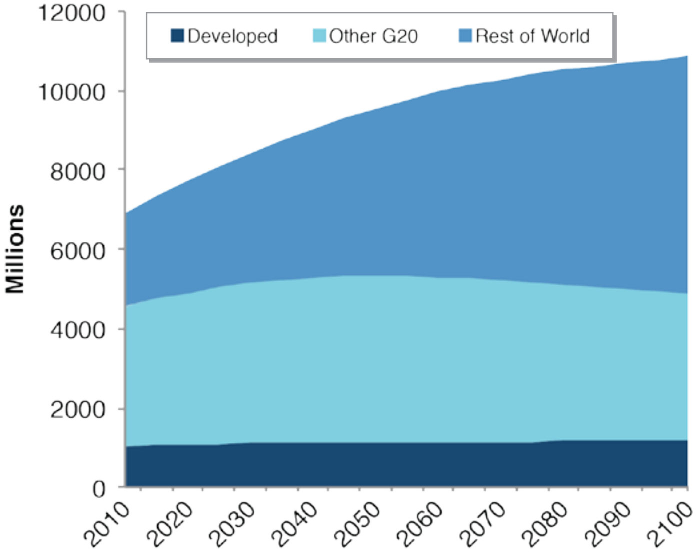


Figure 2. World Population

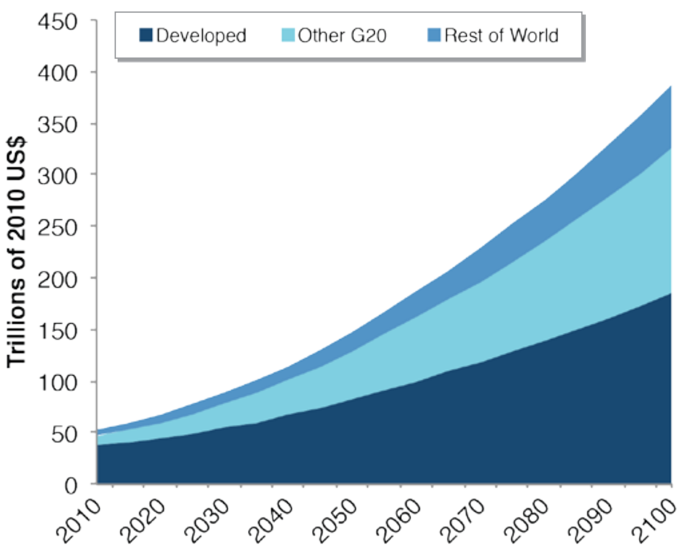


Figure 3. World GDP

Box 3.

INDCs of Major Countries Submitted by Mid-August of 2015 for Consideration at COP21

Major countries submitting INDCs (Intended Nationally Determined Contributions) ahead of COP21 are listed here, along with the policies and measures we have represented in our projections. In Europe, the U.S., China, and Japan we have attempted to approximate the effect of **transportation** and **electricity** sector measures the countries are pursuing. By themselves, these may not achieve the emissions reduction targets proposed in their INDC, so in addition we impose a national **emissions cap** to meet the emissions target.

Region	Policies and Measures		
	Emissions cap	Transport policies	Electricity policies
USA	27% GHG reduction by 2025 onward relative to 2005	30 miles per gallon (mpg) for all private vehicles by 2030	No new coal-fired power plants without CCS after 2020; support to wind and solar power to triple production in 2030 relative to 2010
EUR	40% GHG reduction by 2030 onward relative to 1990	45 mpg for all private vehicles by 2030	No nuclear expansion; support to wind and solar power to triple production in 2030 relative to 2010
CHN	CO_2 peaks by 2030; coal consumption does not exceed 4.2 billion tons		No new coal-fired power plants without CCS after 2030; support to wind and solar power to quadruple production in 2030 relative to 2010, quadrupled 2015 nuclear production by 2030
JPN	24% GHG reduction by 2030 relative to 2010		Limited nuclear production in 2015 and gradual restart of nuclear reaching 2010 levels by 2050
RUS	27% GHG reduction by 2030 relative to 1990		
CAN	21% GHG reduction by 2020		
ANZ	13% GHG reduction by 2030 relative to 2010		
MEX	11% GHG reduction by 2030 relative to 2015		

Recap of COP21 & Needed Progress to Achieve Nationally Determined Contributions

The Changing World

Based on U.N. median estimates (U.N., 2013), the world's population will pass the 9.6 billion mark by 2050 and reach 10.8 billion by the end of the century. These projections show that much of the growth will happen in developing regions like the Middle East, Africa and Latin America, our *Rest of the World* group in **Figure 2**. Population levels, after rising until about 2035 in the *Developed* and *Other G20* regions, stabilize and drift downward, driven to a large extent by trends in China's population.

Our estimate of near-term growth in GDP was based on the 2015 International Monetary Fund Outlook (IMF, 2015). We then developed a long-term projection for each EPPA region (**Figure 3**). At least in terms of short-term prospects for growth, the picture has worsened for most regions over the past year, according to more recent IMF projections (IMF, 2016). Whereas in 2015, global growth for 2015 was projected to be 3.5%, rising to 3.8% in 2016 and 2017, the estimate for 2015 is now 3.1%, recovering to 3.2% in 2016 and 3.5% in 2017. A big part of the slower growth outlook is rebalancing of the Chinese economy that has led to a significant slowdown there, and slow growth in many emerging nations, especially those dependent on natural resource exports, for which prices have plummeted. Oil export-dependent countries in the Middle-East and Russia, and ore and agricultural exporters such as Brazil are major examples. If we were to revise our projections in line with these trends and assumed they were a longer-term phenomenon, then the catch-up of the *Other G20* to the *Developed* region and the modest gains in the *Rest of the World* would likely erode somewhat. But given that economies can falter and then turn around and boom for a decade or more, significantly revising a century-long projection on one additional year's observation is likely foolhardy. Nevertheless, the IMF's April (2016) Outlook subtitle—"Too Slow for Too Long"—may capture the general feeling among economic forecasters that recovery has generally not gone according to expectations. Thus, over the longer term, expectations may need to be adjusted.

Based on these population and GDP projections, we introduced policies and measures into our model that captured, as best we could, our interpretation of the Intended Nationally Determined Contributions of major emitting nations as announced through August of 2015 (**Box 3**).

Global Energy & Emissions

The combination of economic and population growth with energy and greenhouse gas policies and measures results in energy forecasts for the world and three broad country groups as shown in **Figure 4**.

Growth in energy use in our projection is led by the *Other G20* nations, which reaches more than 400 exojoules (EJ) by 2050. As in-

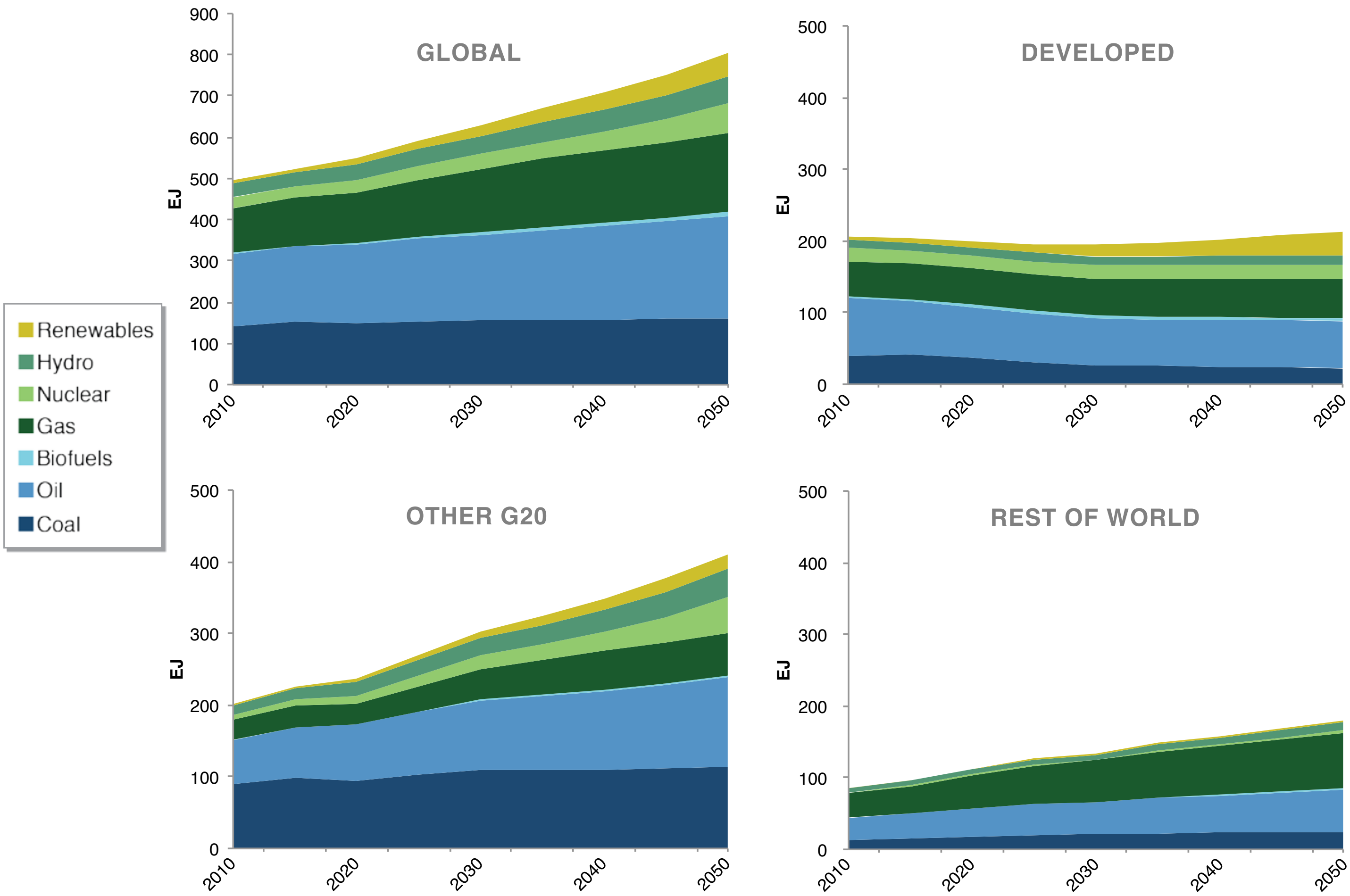


Figure 4. Global and Regional Primary Energy Use

dicated in Box 3, we approximated a mix of policies and measures that affect the fuels and technologies we project, rather than simply applying a carbon price in a region in order to generate the Nationally Determined Contribution (NDC) emissions level. Our assessment of likely measures that many countries would use to meet their NDC pledges tends to favor renewable electricity sources and greater vehicle fuel efficiency.

As noted, we have not updated these projections from the 2015 Outlook. While global totals for 2015 have not been substantially affected by developments over the past year, there have been some important regional developments (**Box 4**).

Under these economic and policy assumptions, total GHG emissions from all sources of human activity (energy, industry, agriculture, waste and land-use change) in 2100 are projected to reach 78 Gt CO_2-equivalent (**Figure 5**). We sum emissions of different gases by converting to CO_2-eq using Global Warming Potential (GWP) indices (**Box 5**). The 78 Gt is a more than 60% increase from the 2010 level. Total fossil fuel CO_2 emissions reach 52 Gt by 2100, about a 70% increase from 2010. Fossil fuel CO_2 emissions at the end of this century still constitute a majority of total GHG emissions on a CO_2-equivalent basis (about two-thirds).

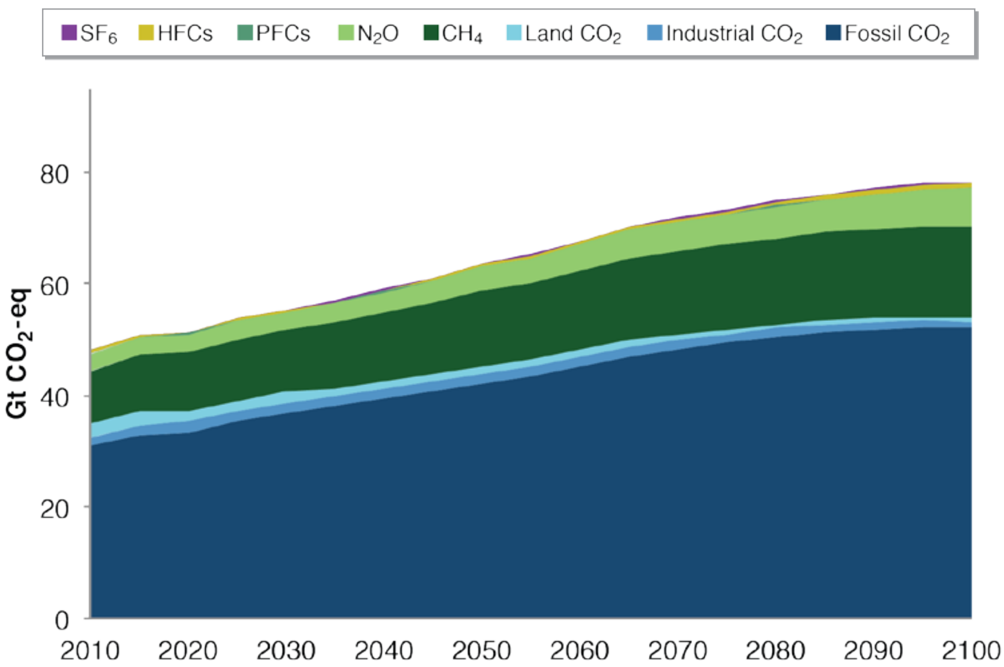


Figure 5. Global Greenhouse Gas Emissions

Climate Implications

While COP21 pledges look ahead to slow growth in emissions, GHG concentrations continue their inexorable rise. Kyoto gases (**Figure 6**)—those included in the emission targets specified under the Kyoto Protocol—reached over 460 ppm CO_2-eq in 2016, and CO_2 concentrations are over 400 ppm. Including CFCs, concentrations are currently over 490 ppm, as shown in Figure 6 and labeled CO_2-eq (IPCC). While new CFCs are not being produced and emitted, concentrations will remain in the atmosphere for a very long time because their lifetimes are thousands of years. The seasonal cycle of concentrations, due largely to strong effects of northern hemisphere vegetation growth and dieback on CO_2, is smoothed to show the underlying trend (for details, see Huang *et al.* [2009], from which Figure 6 is updated). The increase for all three series in Figure 6 has been nearly linear over the period, with CO_2 concentrations increasing by about 1.8 ppm/yr and all GHGs (CO_2-eq-IPCC) increasing at 3 ppm/yr. Note that here we use instantaneous radiative forcing to create CO_2-eq concentrations rather than GWPs because this calculation shows the contribution to warming at a point in time (see Box 5).

A broad convention is that 450 ppm concentrations of GHGs is roughly consistent with 2°C, yet we have not seen that much warming. Two important reasons are (1) the offsetting cooling effect of sulfate aerosols (airborne particles), which is not included in Figure 6; and (2) the inherent inertia in the climate system, which means it will take decades to see most of the warming to which we are already committed. Thus, the fact that we have exceeded 450 ppm CO_2-eq while

Box 4.

Recent Energy Market Changes, and Implications for Near-Term Projections

We decided to not update the basic energy projections from the 2015 Outlook because the exact form of the COP21 commitments and their implementation remain uncertain, thereby limiting the value of further speculation based on minimal new information. That said, there have been some regional changes in energy production and use, due to underlying economic forces, that are worth pointing out. The projected global totals from the 2015 Outlook are in a general agreement with the data from other sources that have been updated more recently, such as the Statistical Review of World Energy (BP, 2016), which provides the most updated estimates of energy use and production, ahead of the IEA and EIA.

Some notable regional differences include China. China's government statistical agency revised upward the country's coal production numbers for the latest decade (NBS, 2013; 2014). For example, coal production in 2012 is higher by about 300 million tons (mt) after the adjustment. This adjustment is equal to about 40% of U.S. coal consumption that year, and with higher base-year estimates of coal production and use, we would expect projections to be higher.

In the U.S., low natural gas prices and existing and expected coal regulation continue to change the electricity mix. From 2014 to 2015 coal generation was reduced from 1582 terawatt hours (TWh) to 1355 TWh, while natural gas generation was increased from 1129 TWh to 1348 TWh (EIA, 2016a). The 2015 Outlook has a somewhat higher number for coal generation projection (1917 TWh) and lower number for natural gas generation (846 TWh) in the U.S., reflecting older base-year data and a projection that does not fully account for the regulatory and economic forces that are likely the reason for the significant shift in relative production of electricity from coal and gas. With significant additional capacity due to the need to meet annual demand peaks, generation from different sources can shift rapidly from year to year as the relative economics of different fuels change.

There are some other regional differences between the projected 2015 numbers and those reported by the energy statistical agencies. Globally, these regional differences are often offset. In the 2015 Outlook, the projected total energy use in 2015 is 154 EJ for coal, 183 EJ for oil, 118 EJ for natural gas and 72 EJ for other energy sources. BP (2016) reports the following primary energy use for 2015: 161 EJ for coal, 182 for oil, 132 EJ for natural gas and 77 EJ for other energy sources.

Box 5.

Comparing Greenhouse Gas Emissions and Concentrations

The radiative forcing of greenhouse gases varies by factors of 1000, as does their atmospheric lifetime. This makes it meaningless to directly add together the radiative effect of tons of CH_4, SF_6, and CO_2: the estimated lifetime of CH_4 is 12.4 years, with 36×10^{-5} $Wm^{-2}ppb^{-1}$ radiative forcing; whereas SF_6 has a lifetime of 3200 years, with $57{,}000 \times 10^{-5}$ $Wm^{-2}ppb^{-1}$ radiative effect; and CO_2 has an effective lifetime on the order of 200 years*, with 1.4×10^{-5} $Wm^{-2}ppb^{-1}$ radiative forcing.

Global warming potentials (GWPs), as reported by the IPCC, integrate the warming effect of each GHG over a given time period to produce an index, CO_2=1.0 by definition, that can then be multiplied by the number tons of that GHG to approximate how much CO_2 it would take to create an equivalent amount of warming. Methane's GWP is 28, so 1 ton of methane is "equivalent" to 28 tons of CO_2; this is traditionally designated as tons of CO_2-eq. In addition to allowing tons to be more sensibly added together, GWPs also offer an improved guide to policy and economic decision-making; if one is willing to pay $10 per ton to abate CO_2 emissions, then one should be willing to pay up to $280 per ton for methane abatement, as the same reduction in warming is achieved.

Unfortunately, these indices are necessarily an approximation. One issue is the time period of integration. The IPCC reports 20-, 100-, and 500-year GWPs—policymakers have focused mostly on the 100-year values. Even the 500-year values truncate the effects of gases that will remain in the atmosphere for thousands of years, and so the shorter the integration period, the higher the GWP for shorter-lived species. As reported in the IPCC's 4th Assessment Report (AR4), methane's 20-year GWP is 72, its 100-year GWP is 25, and its 500-year GWP is 7.6.

Scientists calculating GWPs also have revised their calculations and include at times some of the indirect effects of the gas, especially in the case of methane. Methane's 100-year GWP was 21 in early IPCC reports and has now risen to 28. We have used the most recent IPCC GWP estimates, a revision from our previous Outlook, which used GWP estimates adopted by the U.S. Environmental Protection Agency and included in the IPCC's First Assessment Report. Here, we compare the IPCC's AR5 estimates to the AR4 estimates.

We only use GWPs for reporting purposes such as in Figure 4, and to represent the relative economics of abatement. We use GWPs without climate-carbon feedback, as they reflect better our model setting where nitrogen limitation and changes in terrestrial and ocean uptake are explicitly represented in the IGSM. For simulating the climate effects of emissions, the IGSM does not use GWPs, as it includes the physical processes that determine the lifetime and fate and the radiative effect of each gas. Our use of the new IPPC AR5 GWPs results in differences in reporting of CO_2-eq emissions, but is not a source of difference in our simulation of climate effects.

In contrast, when summing concentrations of different gases in the atmosphere, the common approach is to combine their instantaneous radiative forcing and calculate the equivalent CO_2 concentration that would give the same total radiative forcing. This metric is intended to show how important different gases are in terms of the forcing they are causing at any given time. We use this approach for summing concentrations of different gases as in **Figure 5**.

Gas	IPCC AR4	IPCC AR5
CH_4	25 GWP	28 GWP
N_2O	298 GWP	265 GWP
PFC	7390 GWP	6630 GWP
SF_6	22800 GWP	23500 GWP
HFC	1430 GWP	1300 GWP

*CO_2 does not have a lifetime *per se* and its residence time in the atmosphere varies; 200 years is a rough approximation of the effective residence time.

still seeing relatively small impacts on global temperatures is not an indication that climate response has been overestimated.

The implication of our emissions projections is that CO_2 concentrations approach 710 ppm by 2100, with no sign of stabilizing (**Figure 7**). Our estimates are plotted with CO_2 concentration pathways from the IPCC. These include the four Representative Concentration Pathways (RCP) scenarios (van Vuuren *et al.*, 2011) in dashed lines and the A1FI, A1B, A2 and B1 scenarios from the Special Report on Emissions Scenarios (SRES) (Nakićenović *et al.*, 2000) in dotted lines. The smoothed Mauna Loa record through 2015 (as shown in Figure 6) is also plotted, although it is indistinguishable from the other scenarios, which lie atop it. Our *COP21 Outlook* scenario lies between the SRES A1B and the RCP6.0 scenarios.

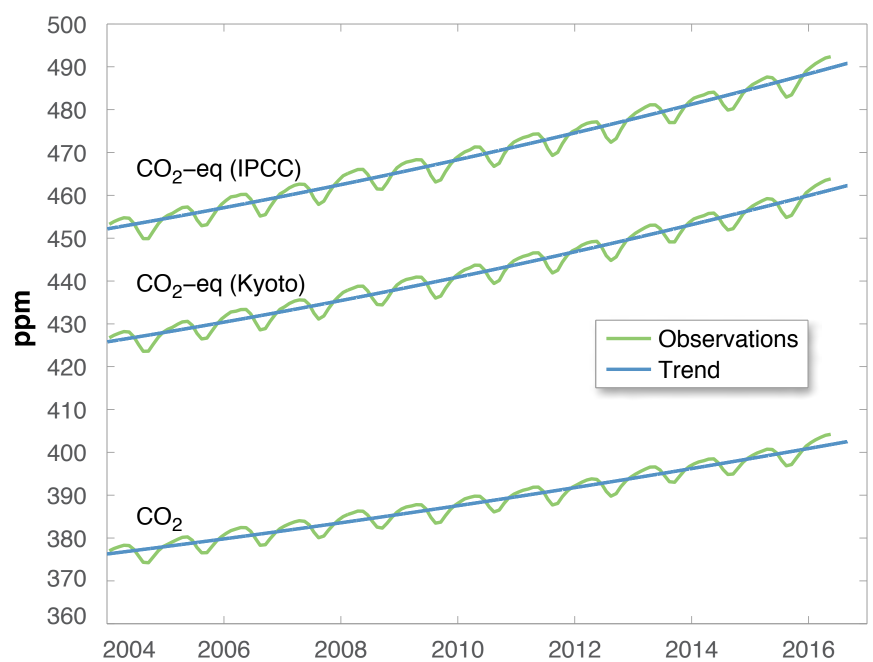


Figure 6. Current Greenhouse Gas Concentrations

There remains considerable uncertainty in the climate response to a given amount of radiative forcing. To incorporate the uncertainty in converting radiative forcing to a temperature increase, we developed three climate scenarios that account for the uncertainty in the Earth system's response to changes in aerosols and GHG concentrations. The climate response of the MIT IGSM to a given emissions level is essentially controlled by three climate parameters: climate sensitivity, ocean heat uptake rate and strength of aerosol forcing (Monier *et al.*, 2013). First, we use a single central value for the rate of ocean heat uptake (Forest *et al.*, 2008). Second, we choose three values of climate sensitivity (CS) that correspond to the 5th percentile (CS=2.0°C), median (CS=2.5°C) and 95th percentile (CS=4.5°C) of the probability density function that was jointly estimated with the ocean heat uptake rate. The lower and upper bounds of climate sen-

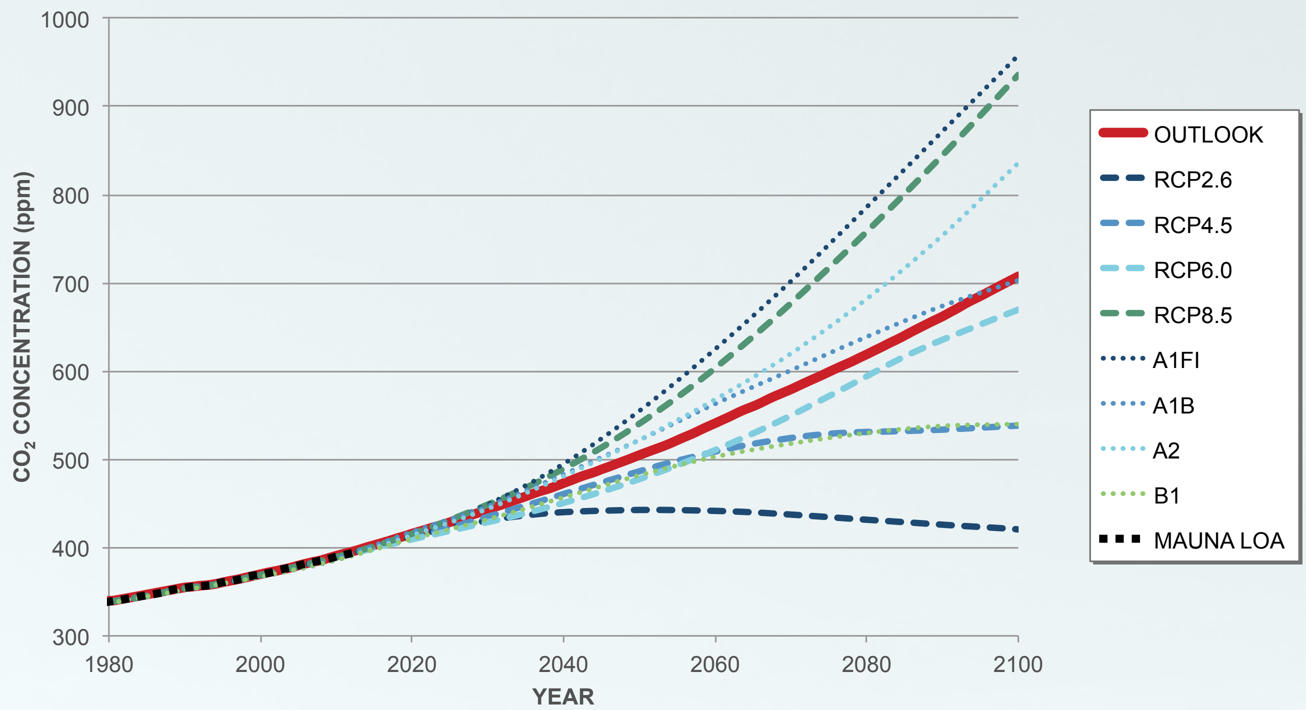


Figure 7. Projected CO_2 Concentrations

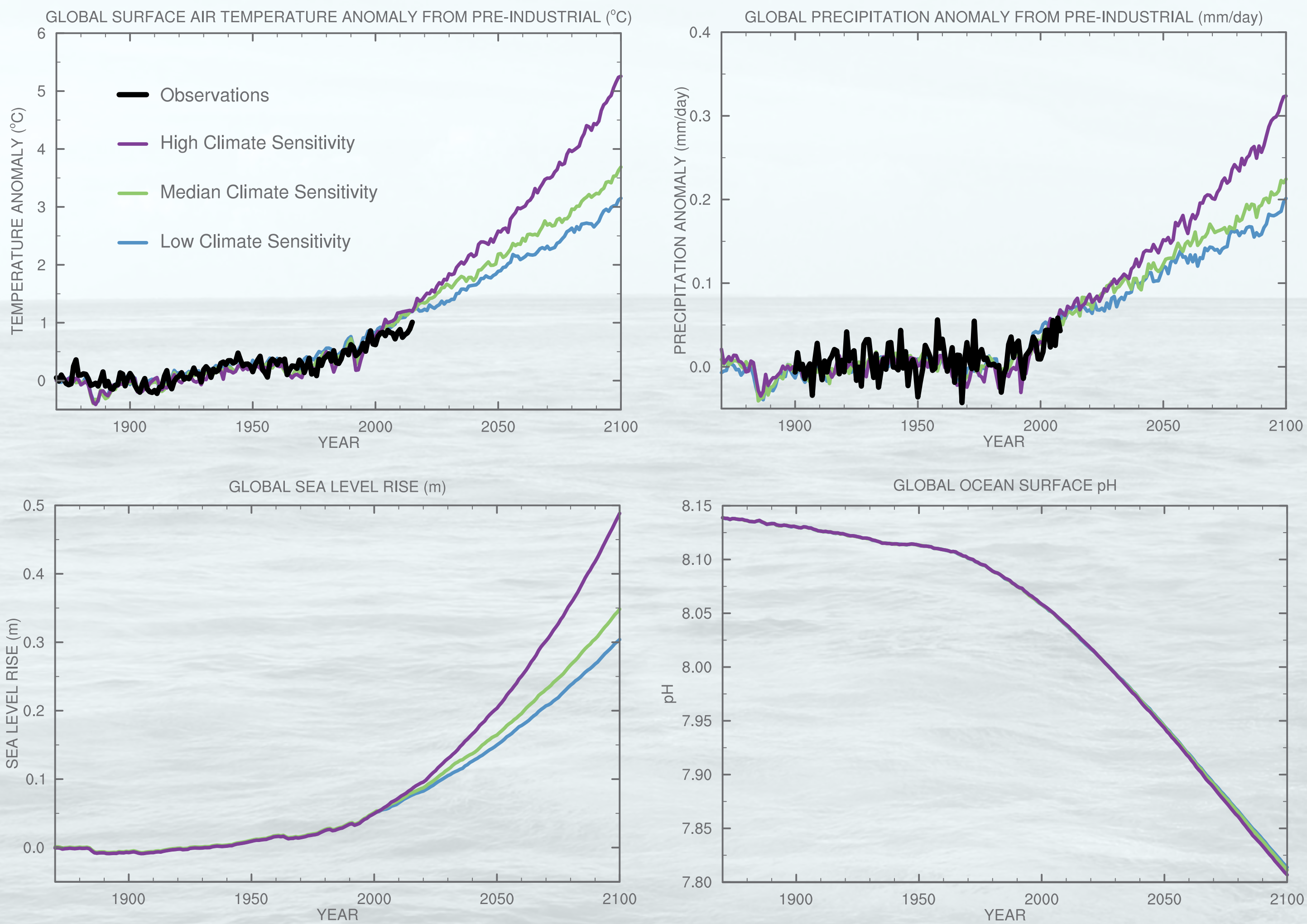


Figure 8. Changes in global mean temperature, precipitation, sea level and ocean surface acidity from preindustrial levels

sitivity agree well with the finding of the IPCC's Fifth Assessment Report (AR5) that the climate sensitivity is likely to lie in the range 1.5 to 4.5°C (IPCC, 2013). Finally, the value of net aerosol forcing is chosen to conform to observed 20th century climate change. The values for net aerosol forcing are –0.25 W/m², –0.55W/m² and –0.85 W/m², corresponding to the CS=2.0°C, 2.5°C and 4.5°C values, respectively.

Using these three sets of climate parameters, the Earth's global mean temperature (**Figure 8**) is projected to increase by 1.9 to 2.6°C (central estimate 2.2°C) by mid-century relative to the preindustrial level (1860–1880 mean), and 3.1 to 5.2°C (central estimate 3.7°C) by 2100. Blue, green and purple lines in Figure 8 represent the means of ensembles with different initial conditions for, respectively, the low, median and high climate sensitivity scenarios.

Figure 8 also shows an increase in the global precipitation anomaly, from 0.05 mm/day in 2010 to a range of 0.2 to 0.32 mm/day in 2100. The precipitation changes represent increases of 3.9 to 5.3% by 2050 relative to preindustrial level, and 7.1 to 11.4% (central estimate 7.9%) by 2100. Global precipitation increases with warming are projected by all climate models as warming speeds up the hydrological cycle, increasing both evaporation and precipitation. Because evaporation and evapotranspiration from plants are increasing and the patterns of precipitation are changing, the increase in precipitation does not necessarily mean that vegetation and water resources are less stressed everywhere, as is explained in the next section on water resources under global change.

Figure 8 also shows that thermal expansion and land glacier melting contribute 0.15 to 0.23 meters to sea-level rise from preindustrial by 2050, and 0.3 to 0.48 meters (central estimate 0.35 meters) by 2100 relative to preindustrial. Melting of large ice sheets will contribute to sea-level rise, but we do not have the capability in our modeling system to project those effects. Thermal expansion, glacier melting, and even more so, ice sheet melting, are slow processes. As a result, the full extent on sea-level rise of warming at any given time will not be observed for hundreds to thousands of years. Sea-level rise is thus nearly irreversible, short of interventions that would actually create cooling.

If emissions ceased completely, radiative forcing and global temperature trends could reverse and would continue to drift downward slowly (see Paltsev *et al.*, 2013). More aggressive interventions in addition to halting all emissions, such as some CO_2 absorption process (tree planting, biomass energy with carbon capture and storage) or geoengineering, could reverse warming more substantially. Given the current trajectory of emissions growth, imagining that we could have zero emissions from fossil energy—and negative emissions if we added tree planting or biomass energy with CCS—would require a massive change in energy infrastructure. Geoengineering carries its own risks and uncertainties.

The time series of temperature changes from the 1901–1950 mean for each continent are shown in **Figure 9**. Green bands represent the range over all climate sensitivity scenarios and initial conditions for the projections over the 21st century; white dotted lines show the mean of the model runs, with five different initial conditions for the median climate sensitivity; blue bands show the range of the simulations over the historical period; and black lines represent observations. All continents are projected to experience large increases in temperature. By 2100, temperature increases in Africa, Australia and South America exceed 3°C while increases exceed 4°C in North America, Europe and Asia. The range of warming is very large, indicating that there is a large uncertainty in the projected warming, and this uncertainty is increasing over time.

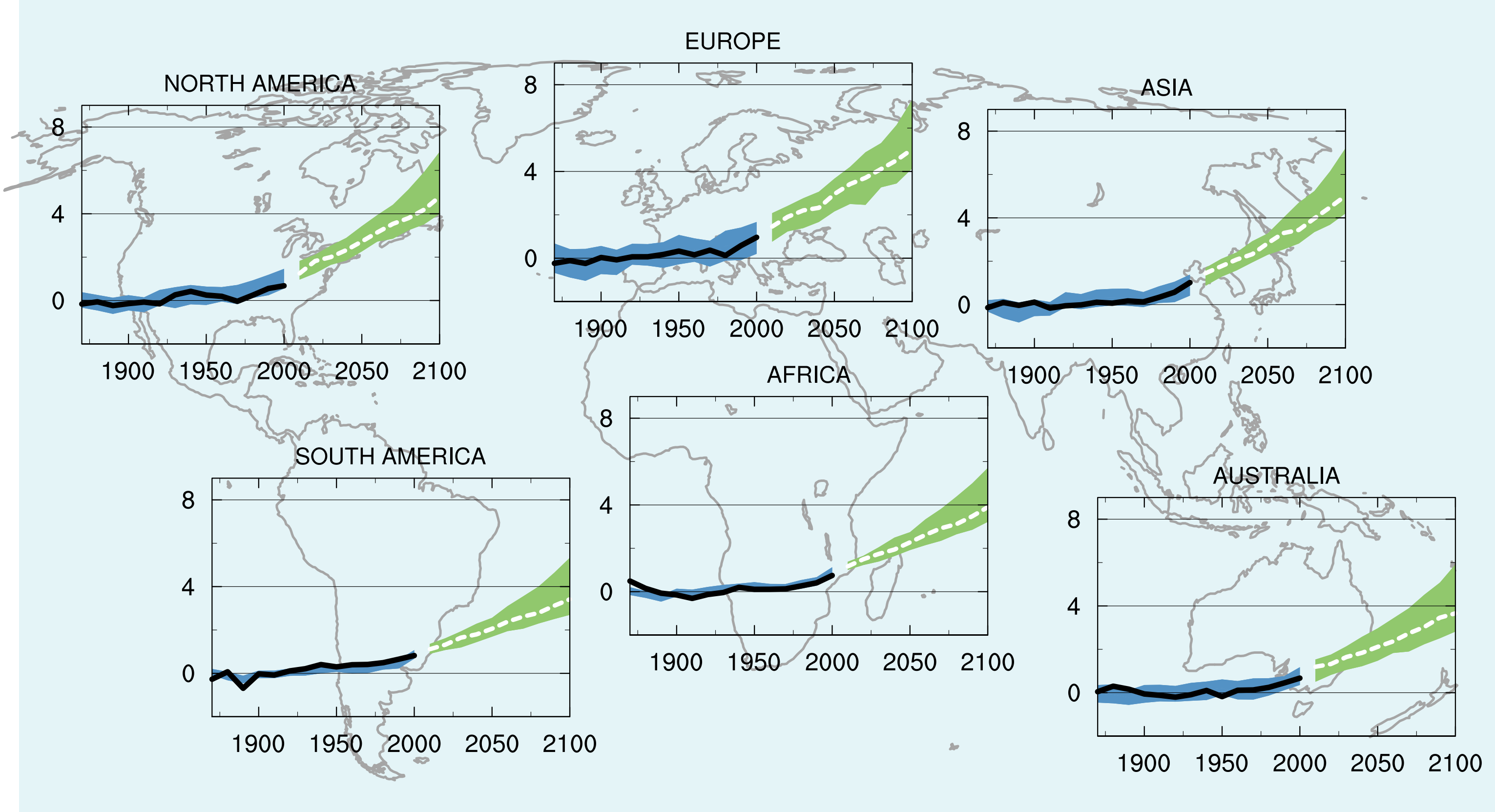


Figure 9. Regional temperature change

Implications for Agriculture & Water Resources in a Changing World

Food and water are two key resources that will be impacted by changes in climate, such as altered temperature and precipitation levels, as well as changes in human systems, such as population growth and land-use decisions. New to this year's Outlook, we include our assessment of how crop yields in breadbasket regions and global and regional water resources will be affected by the changes projected under our *COP21 Outlook* scenario. Of course, the goal of international negotiations is to bring emissions to levels consistent with keeping the rise in global mean surface temperature since preindustrial times below 2°C, and hence to avoid at least some part of the crop-yield and water-resource changes we project.

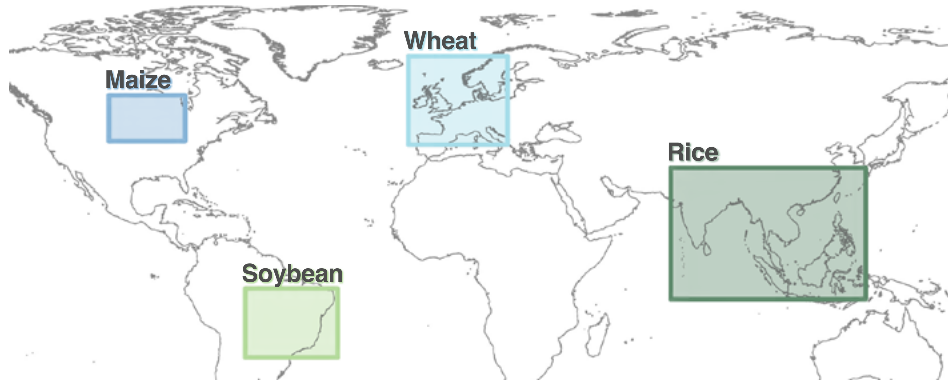


Figure 10. Breadbaskets delineation by crop

Yields for Major Crops in Breadbasket Regions under Global Change

Crops are particularly vulnerable to weather and therefore of prime concern when considering climate change. To assess the impact of climate change on crop yields under our *COP21 Outlook* scenario, we employed statistical emulators of global gridded crop models (GGCM) (Blanc and Sultan, 2015; Blanc, 2016). These emulators are designed to reproduce the effect of weather on crop yields simulated by global gridded crop models. By emulating output from five different crop models (GEPIC, LPJ-GUESS, LPJmL, PEGASUS and pDSSAT), these emulators provide a computationally efficient method to account for crop modelling uncertainty in climate change impact assessments. This exercise focuses on four irrigated crops: maize, rice, wheat and soybean in the major producing regions, called "breadbaskets" (see **Figure 10**).

Weather inputs into the statistical emulators are obtained from the MIT IGSM framework using a pattern scaling method (Schlosser *et al.*, 2012). This method overlays spatial patterns from various General Circulation Models (GCMs) over latitudinal two-dimensional (2D) projections from the IGSM under our *COP21 Outlook* scenario. In this exercise, patterns from nine GCMs are considered in the IGSM to create nine climate change scenarios. Average temperature and precipitation time series for each are provided in **Figure 11** and show that temperature is expected to rise in every region and under all climate change scenarios, whereas precipitation is stationary overall. In using the

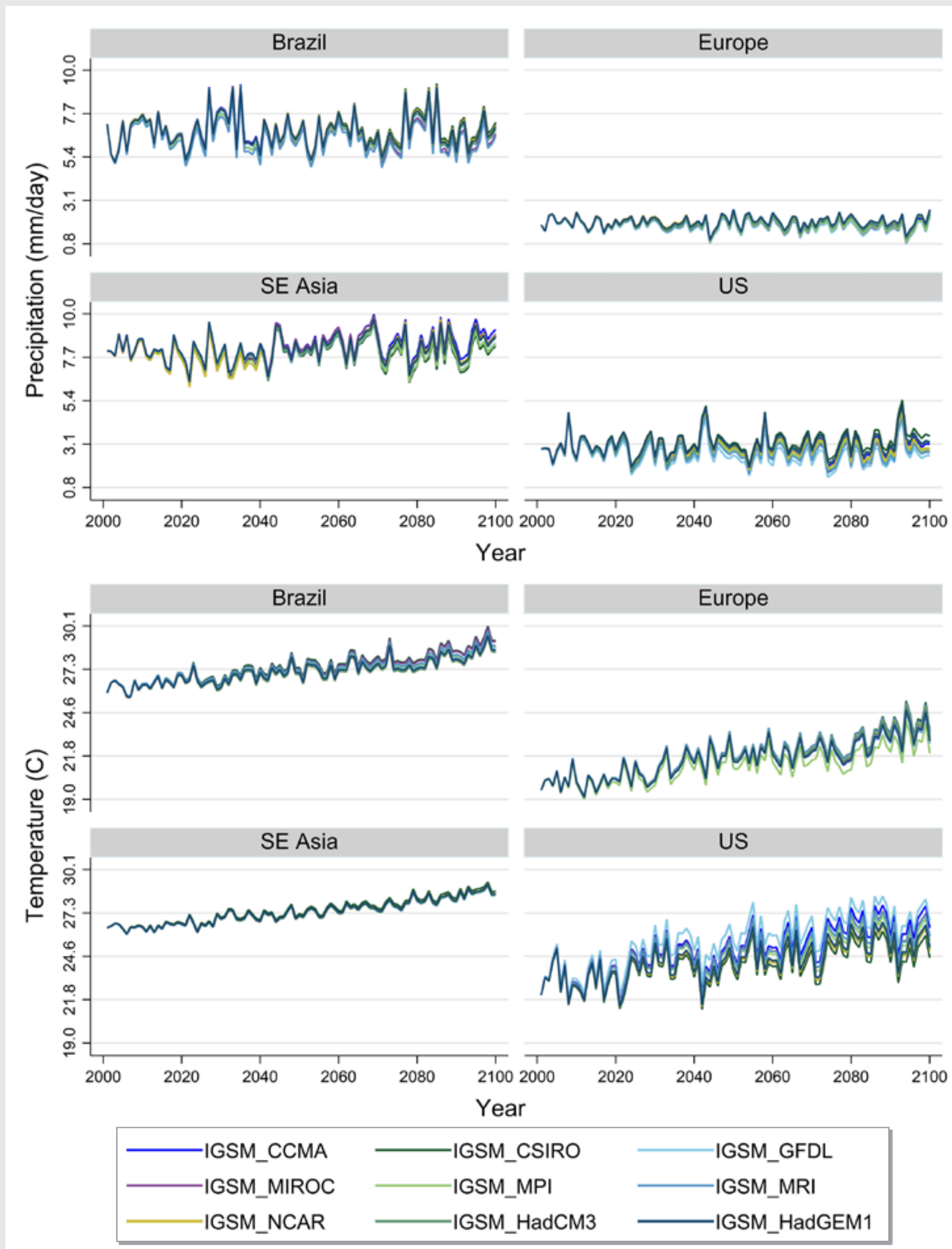


Figure 11. Average temperature and precipitation for the second month of summer in each breadbasket

2D IGSM as a driver of the pattern scaling, this approach imposes an identical pattern of variability through time for latitudinal bands, and hence there is far less difference among these regional climate scenarios than would be the case by comparing output of the GCMs themselves.

Under these climate change scenarios, the impact on crop yields by the end of the century as simulated with the GGCM emulators is largely positive in all regions considered. **Figure 12** shows the crop yields for each breadbasket over time for each crop model for each climate change scenario, as well as the average over all climate change scenarios.

As represented by the extent of the boxes presented in **Figure 13**, the range of yield change varies depending on the GCM considered. However, given the relative uniformity of climate change scenarios considered (Figure 11), the range of crop yields is dominated by the differences among crop model emulators. For rice, for instance, the average yield increase ranges from 0.1 ton/hectare (t/Ha) for the emulated GEPIC model (eGEPIC) to more than 0.8t/Ha for the emulated LPJ-GUESS model (eLPJ-GUESS). By the end of the century, yields increase from between 0.02 tons per hectare (t/Ha) to 0.75 t/Ha for maize, 0.03 t/Ha to 0.9 t/Ha for rice, −0.07 t/Ha to 0.74 t/Ha for soybean, and 0.1 t/Ha to 0.8 t/Ha for wheat, depending on the climate change scenario and crop model.

The differences of impact among emulated crop model projections are also notable at the spatial level. **Figures 14 to 17** show the change in yields between the present (period 2001–2010) and the end of the century, averaged over all climate change scenarios for each emulated crop model. For maize in

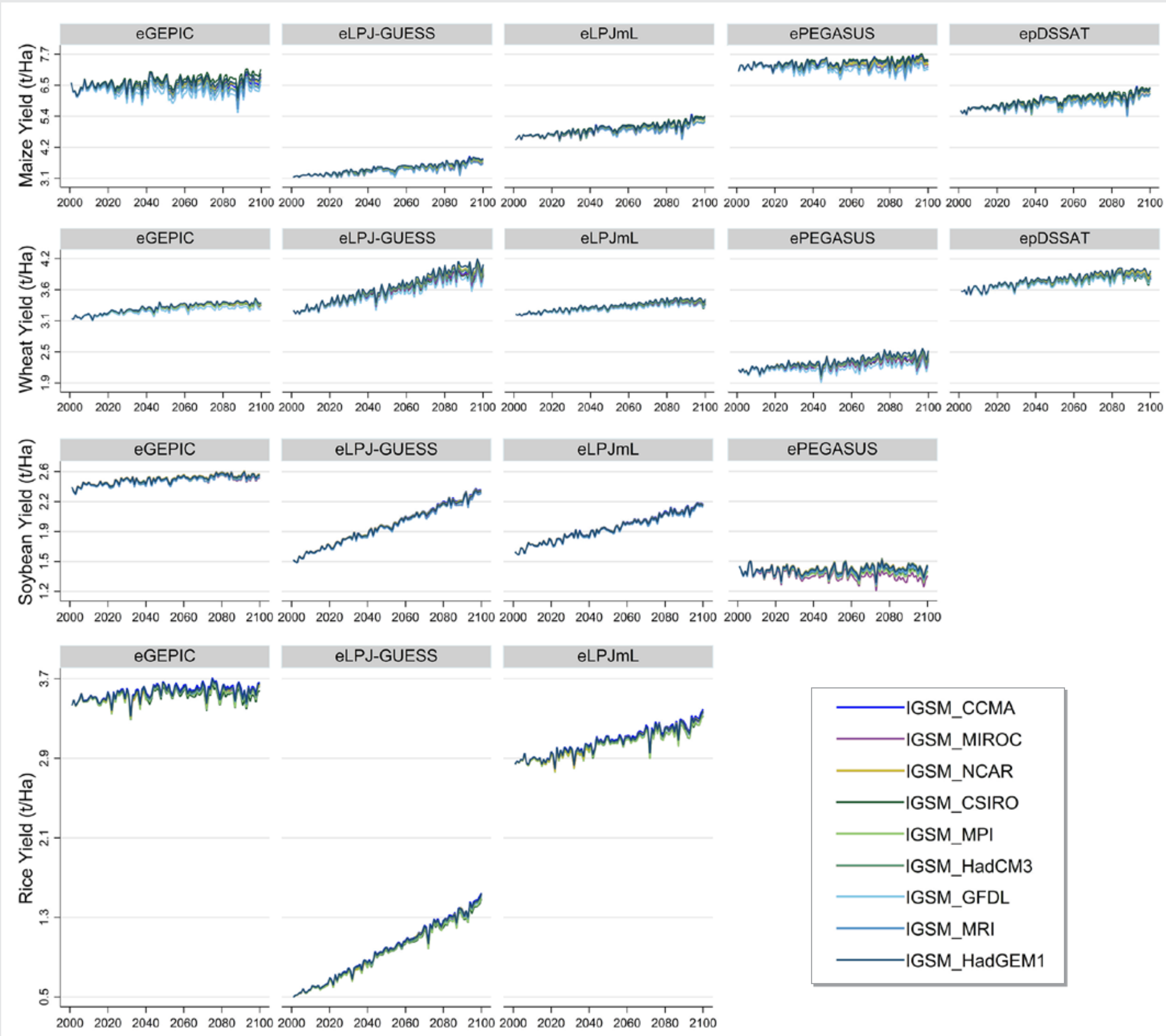


Figure 12. Average crop yields across emulators for each breadbasket for the period 2001–2100

the U.S., the maps show a larger increase in yields in the north than in the south of the breadbasket area. For the emulated PEGASUS model (ePEGASUS), the south–north divergence is the most pronounced, with a large decrease in the south and large increase in the north. A similar phenomenon is also observed for wheat in Europe. Under such conditions, maize and wheat production show a shift northward to benefit from better growing conditions. For soybean and rice, the divergence of impact between emulated crop models is larger so conclusions are less clear, although all models project an overall beneficial effect on upland rice in Southern China.

A large share of the beneficial impact of climate change can be attributed to increases in CO_2 concentrations, which improve crop water-use efficiency and crop productivity. When not accounting for CO_2 effects, crop yields are reduced by between 8% for maize and 33% for rice.

While the effect of CO_2 will certainly benefit crops, it will also benefit weeds, thus increasing competition for nutrients and water. There is also evidence that while crop yield increases, the actual nutrient content of the crop in terms of protein or other nutrients may decline. Thus, the yield gain in tons due to CO_2 fertilization may overestimate the gain in actual feed or food value. These effects are not accounted for in our current crop modeling framework.

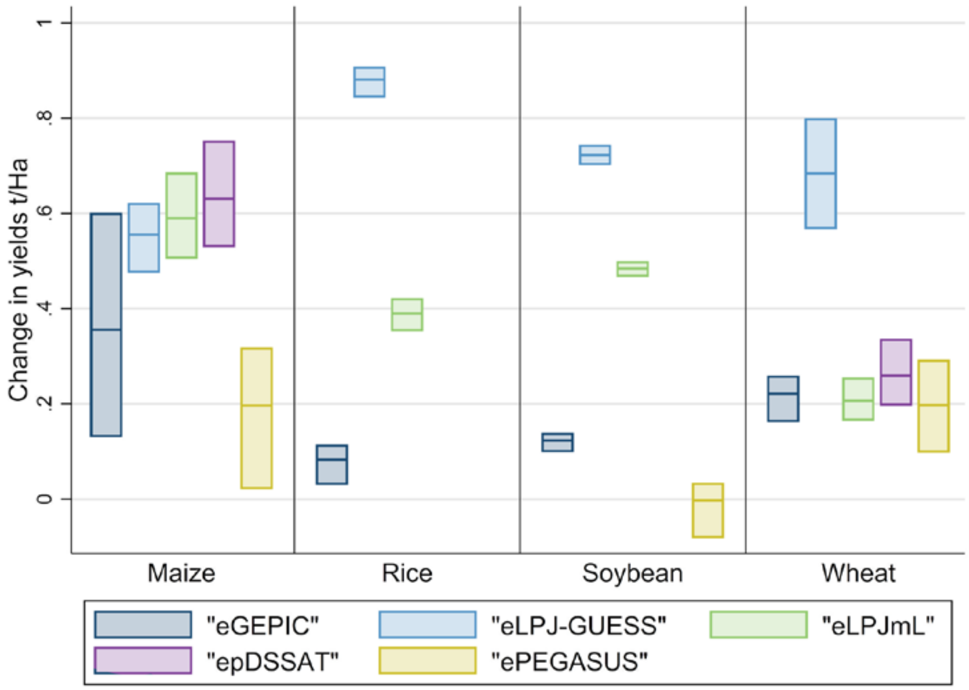


Figure 13. Range of climate change impacts on yields by crop and crop model (period 2091–2100 compared to period 2001–2010). Box contours represent the range of impact across climate scenarios and the center line represents the average impact

It is important to note that while climate change may advantage some areas, as seen above for the major breadbaskets, climate change-driven extreme heat and drought are likely to increase the frequency of major crop failures. The strong gradient in yield impacts within the breadbasket regions as projected by some of the emulators provides evidence of this and suggests that significant relocation of cropping activities may be needed to take advantage of the overall yield gain. In addition, the GGCMs, while a major advance in crop modeling and climate change in that they can project a rich spatial pattern of change that was heretofore impossible, are still quite new and require further calibration and development. As evidence, all of these models significantly under-predict for current crop yields in most of these regions. While this comparison is not completely apples-to-apples because actual crops are not grown uniformly across these breadbasket regions as simulated here, a comparison with actual current yields is suggestive.

For 2015, the GGCMs predict a range of ~3.0–6.5 t/Ha for maize in the U.S. vs. actual 2014/15 yields of 10.7 t/Ha; ~2.0–3.6 t/Ha for wheat in Europe vs. actual yields of 5.9 t/Ha; ~1.4–2.5 t/Ha for rice in Asia vs. actual yields of 3.2 t/Ha in Southeast Asia, 3.8 t/Ha in South Asia and 6.8 t/Ha in China; and ~0.5–3.6 t/Ha for soybean in Brazil vs. actual yields of 3.0 t/Ha. Actual 2014/15 yields are from the USDA (2016). Only for soybean does the projected current range overlap the actual yield in 2014/15. Note that the USDA data are for total rice and our yield simulations are for upland rice only, where yields tend to be lower.

It is arguable that while the models may not explain current actual yields well, they may still be capturing the effect of weather on yield. However, one would clearly have more confidence in the projections if the models could better explain current yields. This likely requires the incorporation of far better data on management practices such as specific characteristics of cultivars used, including the most recent advances in variety development, fertilizer use and other management tools. Given that this field is quite new, it seems likely that more effort in developing these models will result in rapid advances in their performance.

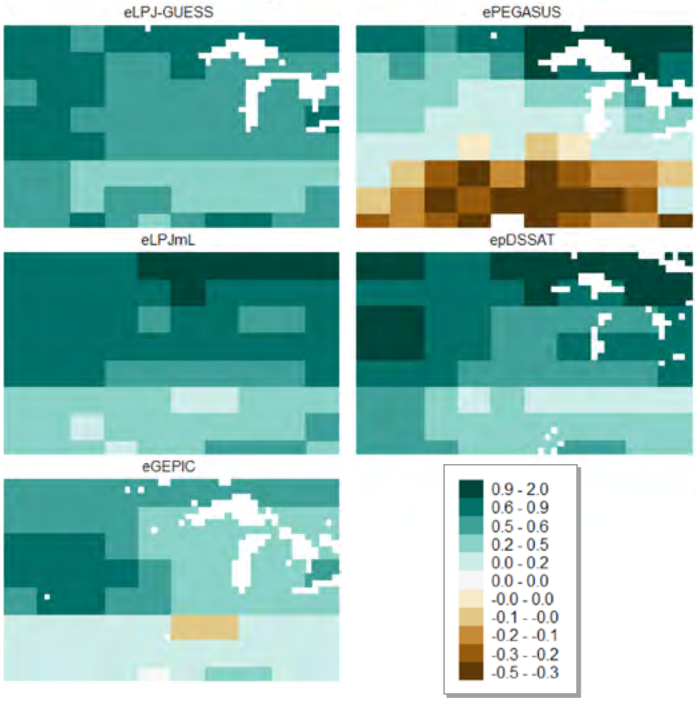


Figure 14. Future changes in maize yields over the U.S. breadbasket (in t/Ha) (period 2091–2100 compared to period 2001–2010), averaged over climate change scenarios

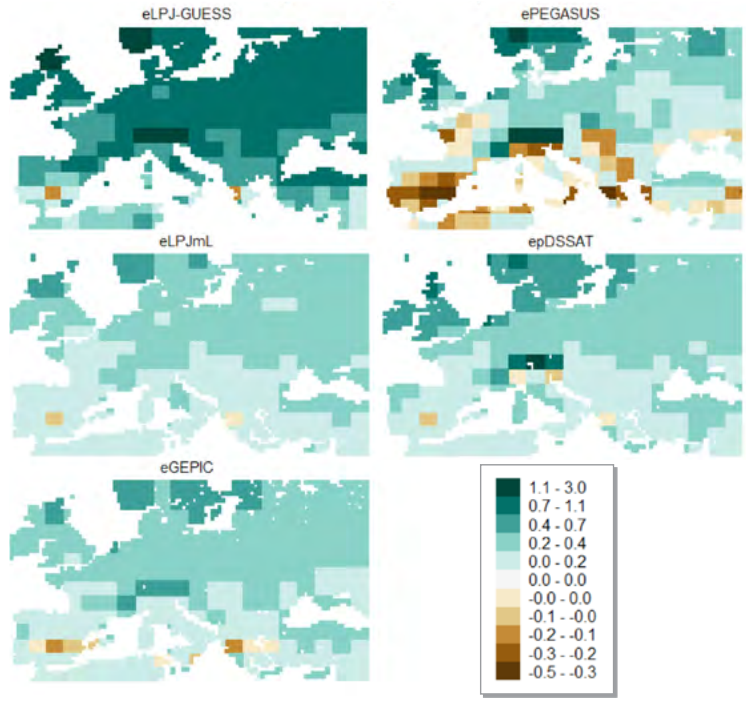


Figure 15. Future changes in wheat yields over the European breadbasket (in t/Ha) (period 2091–2100 compared to period 2001–2010), averaged over climate change scenarios

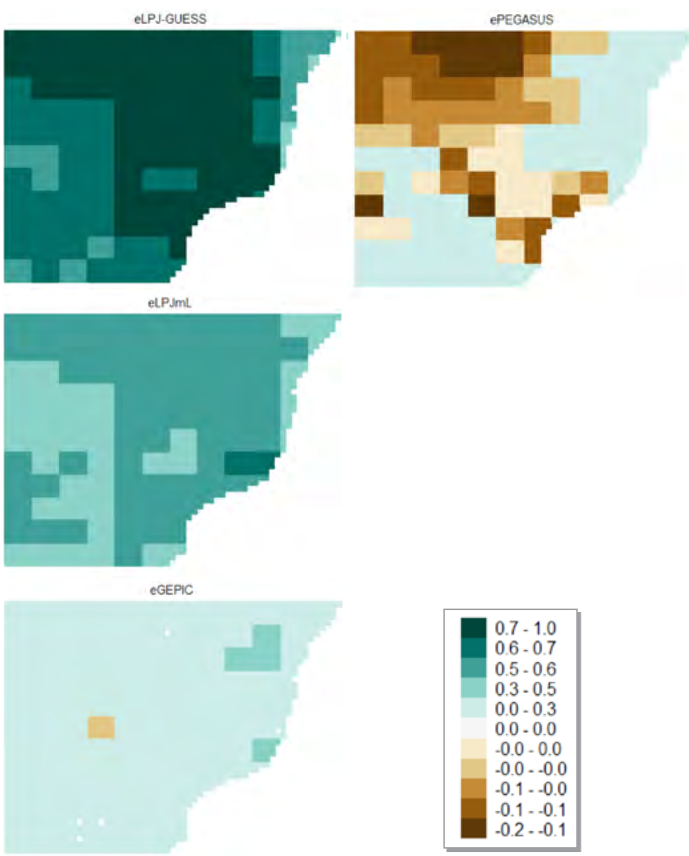


Figure 16. Future changes in soybean yields over the Brazilian breadbasket (in t/Ha) (period 2091–2100 compared to period 2001–2010), averaged over climate change scenarios

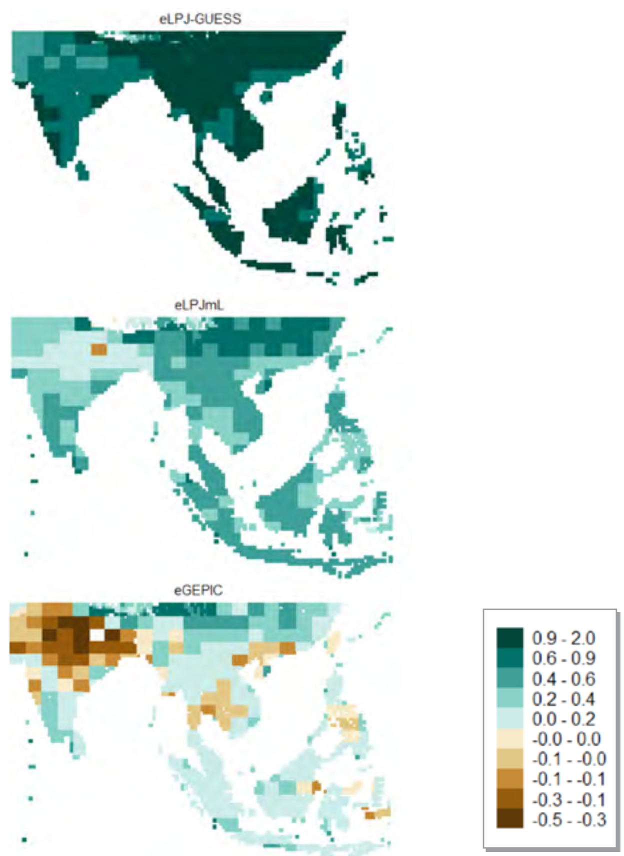
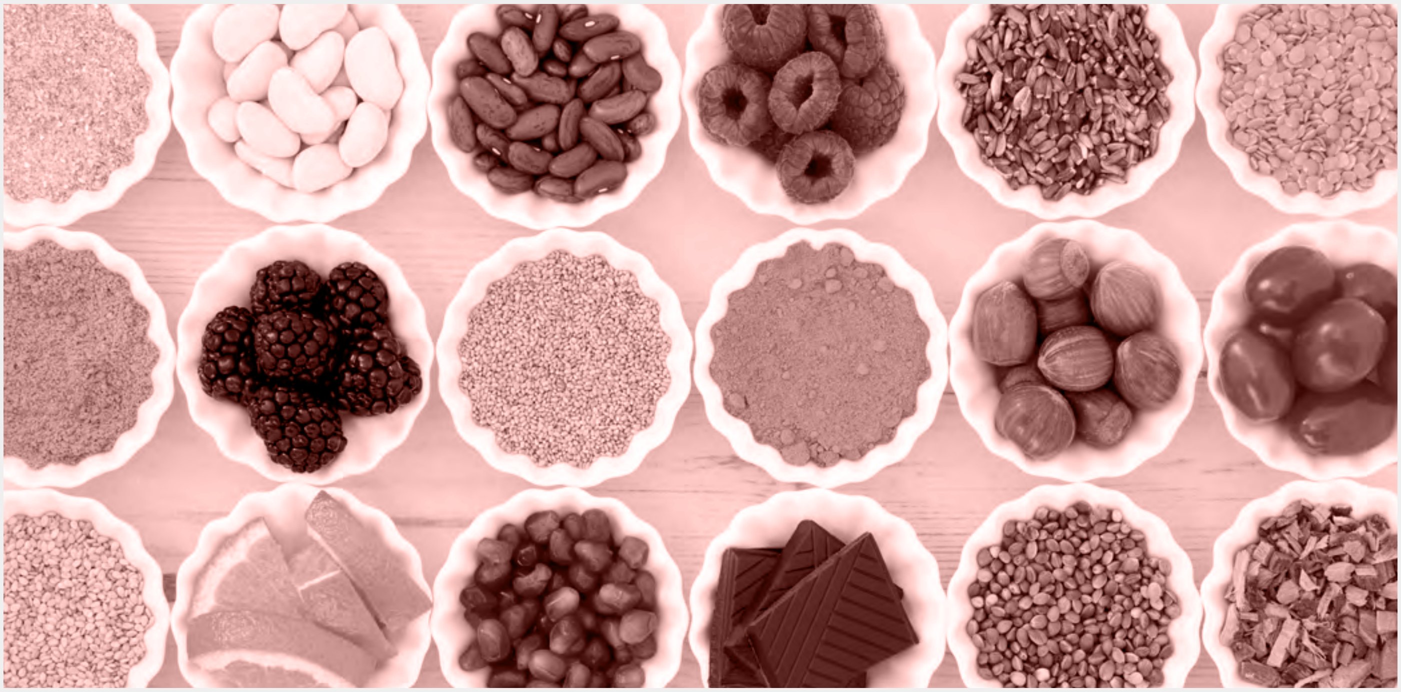


Figure 17. Future changes in rice yields over the South-East Asia breadbasket (in t/Ha) (period 2091–2100 compared to period 2001–2010), averaged over climate change scenarios



Box 6.

Food Challenges Ahead

By John Reilly

According to United Nations experts, enough food is produced around the globe to enable everyone to be adequately nourished and lead healthy and productive lives. And yet, approximately 926 million people continue to go hungry, especially the rural poor in developing countries. The reasons for this are manifold, ranging from natural disasters and extreme storms to war and poverty. Identifying and implementing viable solutions to the problem will become even more urgent over the next 35 years, as the global population soars from today's 7.3 billion to an estimated 9–10 billion, and the demand for food is expected to more than double.

Agriculture faces the challenge of meeting that demand even as it must reduce its environmental footprint and adapt to a changing environment. As it stands now, the Earth's atmosphere and waterways are on the front line, and climate change, tropospheric ozone, and water availability are threats to continued growth in yields.

Land use and agriculture (including forestry) account for an estimated 24% of planet-warming greenhouse gas emissions (although land sequestration offsets an estimated 1/5 of that total). Land-use change is an important source of carbon dioxide, although when properly managed, it could be a sink. The agriculture sector is the biggest contributor of nitrous oxide (largely from fertilizers) and methane (primarily from rice cultivation, ruminants and manure management), accounting for an estimated 85% and 50%, respectively, of emissions of these gases from human activities.

In addition, soil erosion resulting from crop cultivation, along with the nutrients carried with it, has degraded water quality in streams, lakes and coastal waters. In the U.S., the Gulf of Mexico and Chesapeake Bay are among the most seriously impacted coastal ecosystems. Nitrate contamination of groundwater from fertilizer use is also a concern. As efforts proceed to reduce these impacts, agricultural practices will need to adapt.

On the other side of the ledger, increasing levels of tropospheric ozone may continue to threaten future yields unless global precursor emissions are brought under control. Tropospheric ozone damages the leaves of crops, especially at early stages of growth, and is already estimated to reduce yields by 10–12% in China, and somewhat less in the U.S. and Europe. Increasing competition for water resources as population and economic activity expand.

Evaluation of land resources by the U.N.'s Food and Agriculture Organization suggest availability of arable land (under current climate) itself is not a major constraint on food production at least through mid-century, assuming continued yield improvements. There are, however, some wild cards that could vastly impact agriculture in the coming decades. Among these are more ambitious policies to stabilize the climate that may mean large-scale production of biomass energy and major incentives for carbon sequestration in forests. Climate effects on crop yields and on water resources, that would affect availability of water for irrigation, and the uncertainties in these effects, create an added challenge.

Since energy is an important input to agriculture, a global shift away from fossil fuels is likely to boost energy costs and thus make agricultural production more expensive. In addition, the space requirements for biomass energy and re-growing forests to sequester carbon could cut into the amount of land available for crops and livestock production. Agriculture will need to continue to intensify use of available land, getting more output from less land, while at the same time reducing the environmental impacts of the more intensive land-use practices.

Other long-term forces affecting agriculture include the industrialization of agriculture; technological advances; specialization or diversification of farming systems; reliance on a global or local food supply; and the use of land and waterways for urbanization, recreation and ecosystem protection. While some of these forces may make the job of feeding the world more difficult, technology that improves yields and limits vulnerability to environmental change, delivers nutrients efficiently and reduces food waste can hopefully overcome the challenges. At the same time, successful efforts to control climate change and ozone pollution will lessen the adaptation agriculture will need to make. More diversification of farming systems and well-developed international markets can further limit vulnerabilities to local droughts and disasters. And while new technology is certainly welcome, if not essential, adopting today's best practices worldwide can take us a long way.

John Reilly is co-director of the MIT Joint Program on the Science and Policy of Global Change and a senior lecturer at the MIT Sloan School of Management.

Water Resources under Global Change

We have assessed the trends in managed water stress simulated by the Water Resource System (Strzepek *et al*., 2013) within the IGSM framework (IGSM-WRS) under our *COP21 Outlook* scenario. The WRS is forced by the global simulations of climate from the MIT Earth System Model (MESM) as well as the socio-economic drivers from the MIT EPPA model. At each Assessment Sub-Region (ASR), we calculate a Water Stress Index (WSI) as the ratio of total water withdrawals to the total surface water supply (which is the sum of the basin's runoff and inflow from upstream basins). This is one measure of water stress developed by water resource experts. Changes in WSI are relative to the WRS forced by observed historical climate conditions (**Figure 18**). For the purposes of this assessment, we draw from previous work (Fant *et al*., 2016; Schlosser *et al*., 2014; Blanc *et al*., 2014; Strzepek *et al*., 2013) and characterize values of WSI greater than 0.3 as experiencing "moderately" stressed conditions, values greater than 0.6 characterized as "heavily" stressed, values greater than 1 as "overly" stressed (experiencing a water deficit), and values greater than 2 as "extremely" water-stressed.

In this report, we focus on the changes in water stress in the coming decades (and going into the latter half of this century) brought about by our projected climate and socio-economic changes, as well as the total (additional) populations affected by increased stress. We highlight select ASRs to demonstrate sensitivities and interplay between supply and demand. For the *COP21 Outlook* scenario, we consider two plausible yet distinct patterns of climate change that are consistent with patterns projected by major GCMs ("Pattern A" and "Pattern B") and two values of climate sensitivity (2.0, corresponding to the 5th percentile, and 4.5, corresponding to the 95th percentile) to help demonstrate the uncertainty in regional climate change and global climate sensitivity.

Globally, we find that aspects associated with the changes in WSI out to 2050 are quite similar to the results of Schlosser *et al.* (2014). The largest relative increases in WSI are found in Africa (**Figure 19**, all panels), and are primarily the result of large increases in the non-agricultural water-demand sectors (driven by increases in population and economic output). This underscores the finding of Schlosser *et al.* (2014) that adaptive measures will be required, worldwide, to meet surface-water shortfalls—even if climate change were not a factor.

The results also highlight the importance of the uncertainty in regional climate patterns. Comparing the top and bottom panels of Figure 19 (where differences are only a result of the climate-pattern selection), we find the largest differences over North America; basins in Eastern Africa, Southern and Eastern Asia; and Europe. Important to note is that that two climate patterns (A and B) do not necessarily represent the total range of plausible climate outcomes. A more comprehensive sampling of climate patterns is warranted in order to determine the full range of outcomes as well as to assess the likelihood of any particular WSI trend tendency (i.e., increase, decrease or no change).

For some ASRs, increases in precipitation are seen across both regional climate-pattern

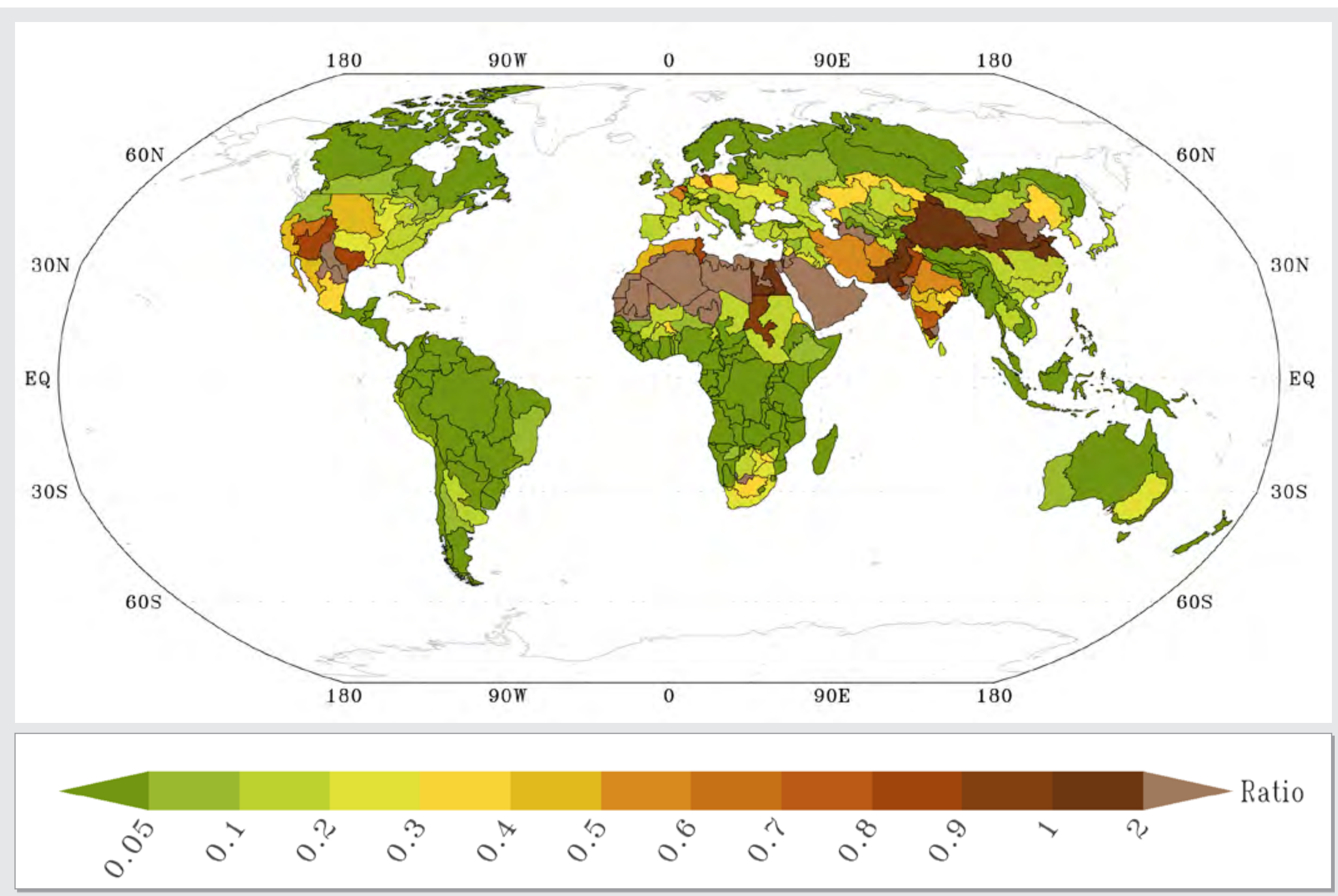


Figure 18. Water Stress Index (WSI, unitless) averaged for the years 2001–2020 from the Water Resource System simulation

and sensitivities considered (e.g., northern Europe and most of Canada), and these increases help to ameliorate the water situation even with increased water demand. For a number of ASRs, however, the increased runoff that results from increases in precipitation (**Figure 20**) is offset by stronger increases in water withdrawals, which results in increases in WSI. This stems from socio-economic growth drivers increasing demand for water. At the same time, there are regions of widespread increases in water stress—primarily located over central parts of Asia, northern Africa and Australia—that are a direct result of decreased runoff. We find that the effect of changes in irrigation demand (**Figure 21**) on water stress are not as extensive as those seen for runoff. For many regions across the globe, increases in irrigation demand range from 5–10% by mid-century, with some of the largest increases occurring over Central and Eastern Europe. During this time period, the impact of climate sensitivity on irrigation demand changes is weak, but the uncertainty in regional climate-change response is more noticeable, particularly over North America. Note that the estimates of increase in irrigation water demand consider only the increased demand on currently irrigated areas. There may be incentives for—or limits on—irrigation where adaptation measures could change which areas are actually irrigated in the future.

Looking closer at the Mississippi ASR-Basin over North America (**Figure 22**, top panel), we find that the impact of the regional climate-change response on our simulated changes in irrigation demand plays a strong role in the subsequent evolution of water stress. The simulated trend of water stress tracks closely with that of irrigation demand, and the choice of the regional climate-pattern response can determine the sign of the water stress trend through the middle of the century. Runoff also shows a very strong sensitivity to regional climate change, and can vary both in magnitude and sign of the trend going into the latter part of this century. These controls and sensitivities can show other distinct features when looking at basins around the globe. In particular, over southern India for the Cauvery ASR-Basin, the seventh largest basin in India (Figure 22, bottom panel), the trends in runoff and water stress track closely to one another (inversely). The relative change and trends in irrigation demand, while comparatively smaller, still show a notable sensitivity to the regional climate response.

An additional striking feature in the trends for both of these selected ASR-basins is that they are not necessarily monotonic. A tendency for runoff or water stress to change over the next two decades may be followed by a reversal in that trend.

Globally, and in the absence of adaptation that would likely be taken to alleviate at least some of this water stress, these climate scenarios indicate that by 2050 approximately 1.5 billion additional people could potentially experience stressed water conditions worldwide (**Figure 23**). Nearly one billion or more additional people could potentially be living within regions under heavily to extremely-stressed water conditions. The two regional climate-change response patterns results differ in total by about 10%. The strongest impact of the regional climate response is seen in the two highest water-stress categories, with the range of additional population living within basins deemed “extremely stressed” being 150 to 325 million. However, as previously emphasized, the lack of a full sampling of all possible climate-change patterns precludes any rigorous risk quantifications to be made in this regard. These results highlight that adaptive measures will be required worldwide to mitigate water stress.

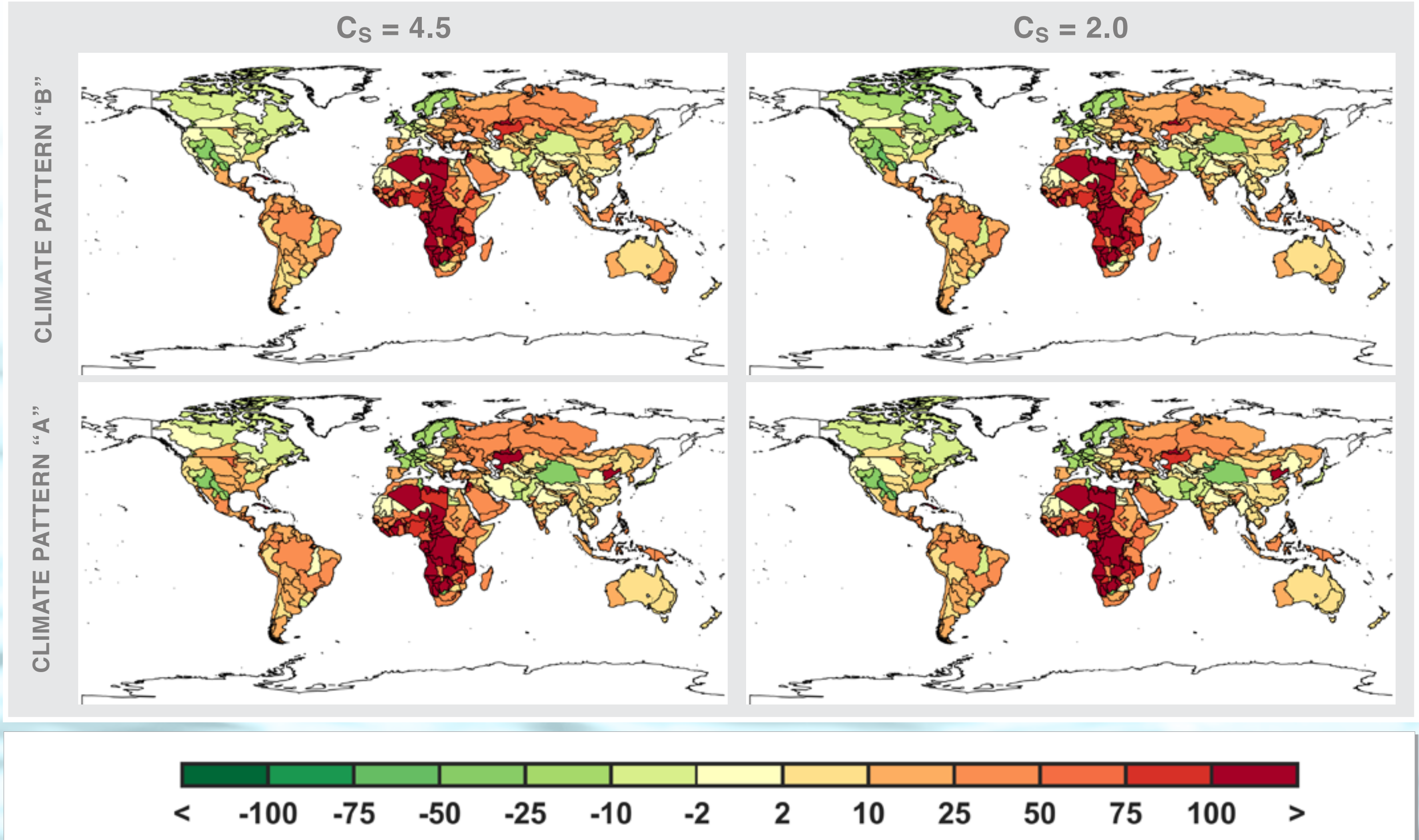


Figure 19. Relative changes (in %) in the 2041–2060 averaged Water Stress Index (WSI) relative to the 2001–2020 averaged WSI results in Figure 18. Simulated by the IGSM-WRS and driven by the climate and socio-economic projections of the *COP21 Outlook* scenario. The left and right columns indicate the impact of a high (left column) and low (right column) climate sensitivity on the global patterns of WSI change. The upper and lower rows highlight the impact of differing patterns of climate change.

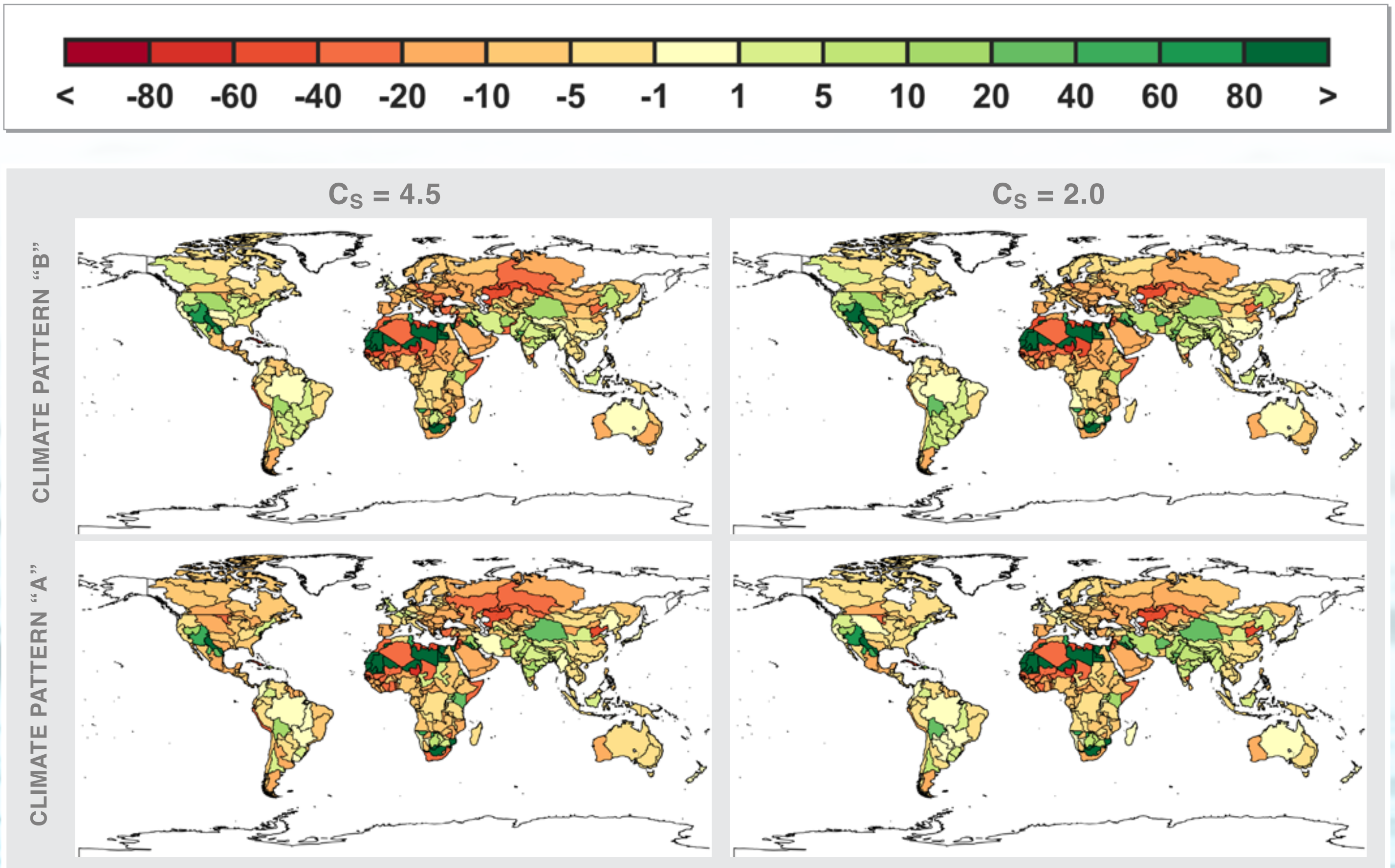


Figure 20. Relative changes (in %) in the 2041–2060 averaged runoff relative to the 2001–2020 average. Simulated by the IGSM-WRS and driven by the climate and socio-economic projections of the *COP21 Outlook* scenario. The left and right columns indicate the impact of a high (left column) and low (right column) climate sensitivity on the global patterns of WSI change. The upper and lower rows highlight the impact of differing patterns of climate change.

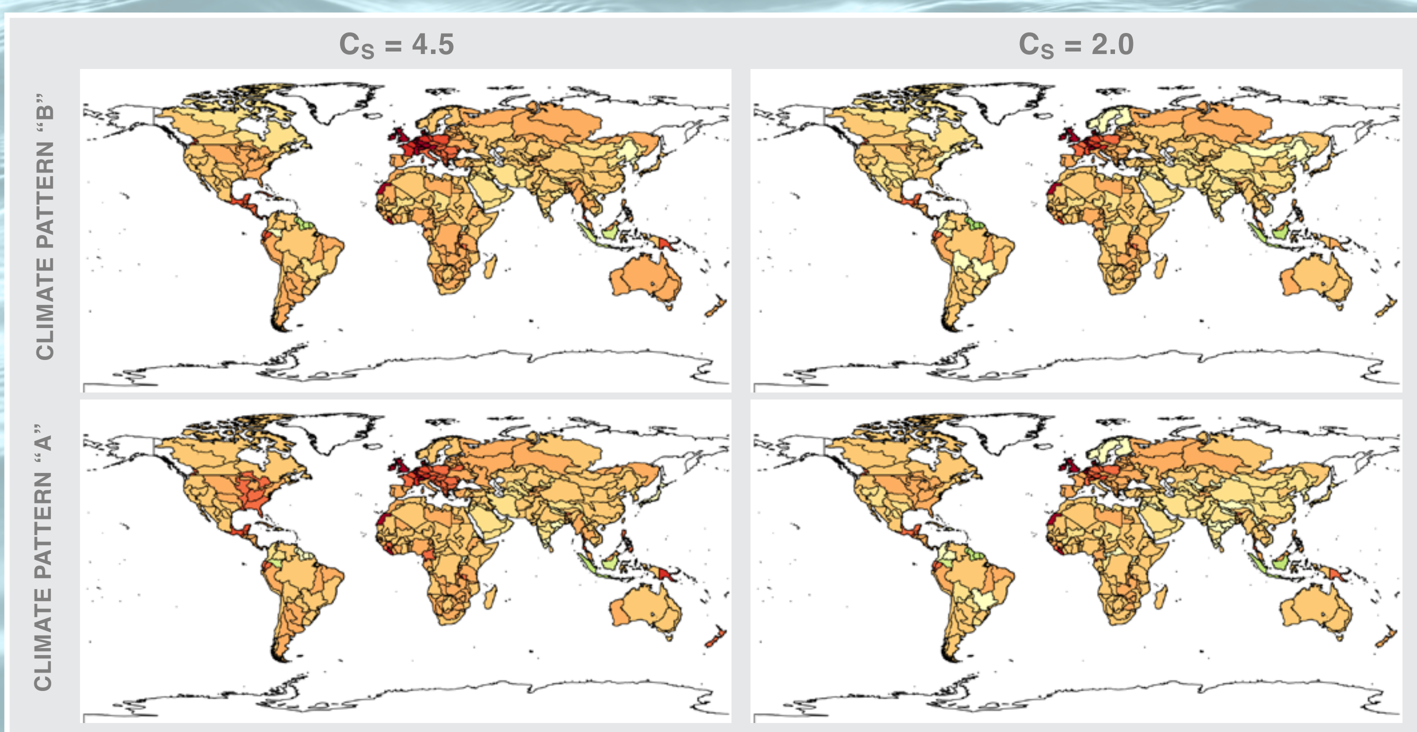


Figure 21. Relative changes (in %) in the 2041–2060 averaged total irrigation demand relative to the 2001–2020 average. Simulated by the IGSM-WRS and driven by the climate and socio-economic projections of the *COP21 Outlook* scenario. The left and right columns indicate the impact of a high (left column) and low (right column) climate sensitivity on the global patterns of WSI change. The upper and lower rows highlight the impact of differing patterns of climate change.

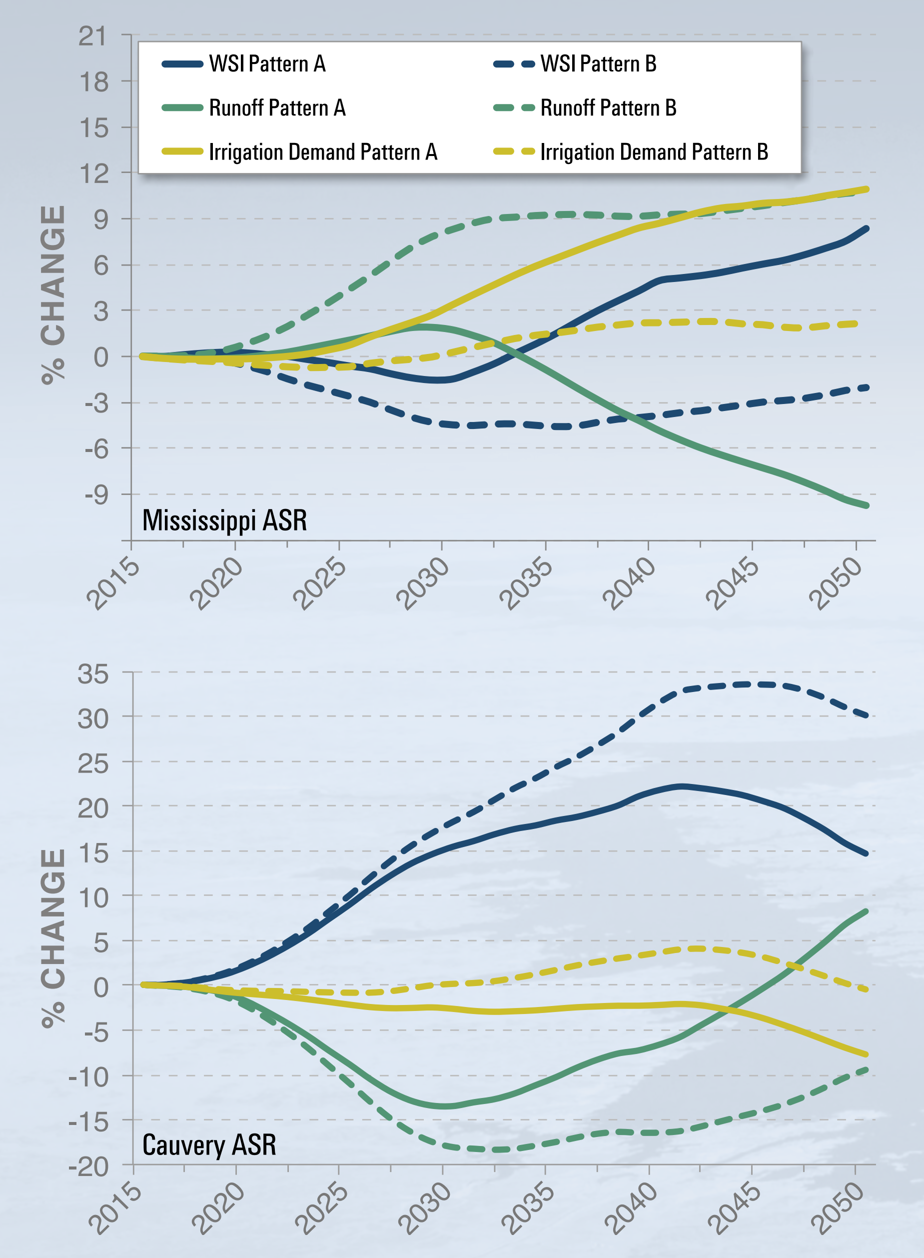


Figure 22. Time-series of changes in WSI (blue curves), basin runoff (green curves), and irrigation demand (yellow curves) for two selected ASR-basins (Mississippi top panel and Cauvery bottom panel) of the global IGSM-WRS framework. The results also illustrate the impact of different climate patterns (denoted by solid and dashed lines) imposed upon the IGSM *COP21 Outlook* scenario. Time-series are smoothed by a 10-year running mean and differences are with respect to the 2006–2015 average. Abscissa values denote the end of the 10-year running-average time-series.

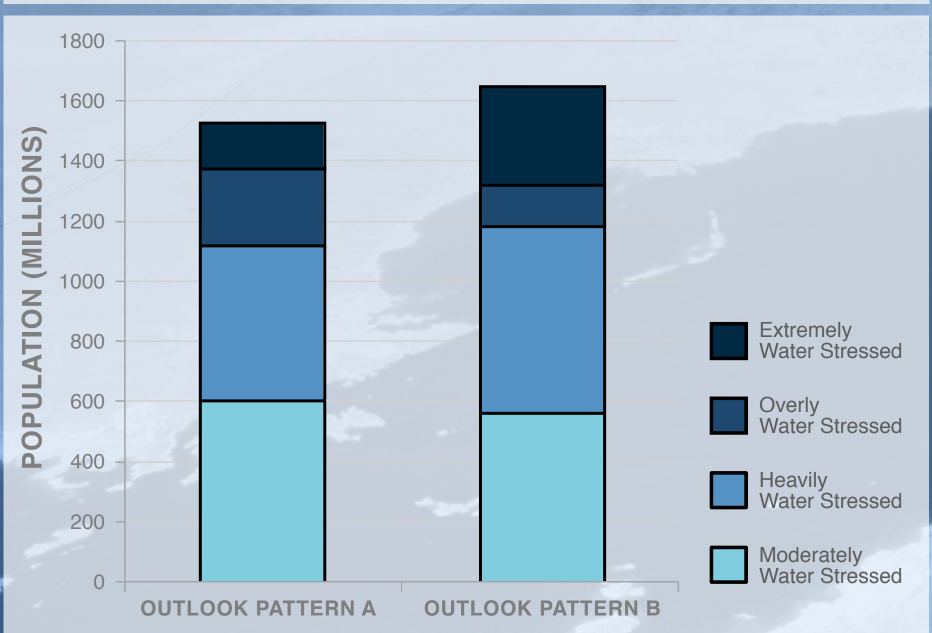


Figure 23. Additional global population exposed to water stress by 2050 relative to population exposure under the 2001–2020 averaged WSI results. The stacked bar chart displays the additional global population (in millions) exposed to water stress for the IGSM-WRS scenarios considered. Water stress is quantified by the water-stress indicator (WSI) for each ASR, and each ASR's population is binned according to WSI categories simulated by the IGSM-WRS.

Box 7.

Water Challenges Ahead

By Kenneth Strzepek

Today's global water resources are subject to an interconnected set of global, regional and local environmental, social and economic pressures. While there is no global water crisis per se, there is a significant and growing number of local and regional hot spots as shown in **Figure 24**. Some regions are now facing water scarcity due to water demands approaching or exceeding the supply provided by the existing water infrastructure. The escalation in demand is due to population increases, economic development, environmental restoration and urbanization.

Shortages occur when the supply cannot be increased for three main reasons: physical water scarcity (lack of fully developed, sustainable surface and groundwater hydrologic resources); economic water scarcity (lack of economic resources to develop the needed infrastructure to boost the water supply from hydrologic resources); and decadal climate variability and climate change (reduction in hydrologic resources and increases in irrigation demands due to changes in precipitation and temperature).

In addition to these classic water supply-demand challenges, the globe is facing a growing conflict over allocation of water among competing social, economic and environmental demands.

For instance, the demand for low-carbon energy sources, particularly renewables, is contributing to increased tensions, particularly in Africa, over priorities in the development of river basin water resources. Development of resources for hydropower already threatens development for irrigation of crops. In the Zambezi basin, full hydropower development limits irrigation development to 30% of its full potential (World Bank, 2010). In addition, demand for low-carbon biofuels can spark division over which to irrigate: biofuels or food.

Another growing conflict is between water for food—which accounts for more than 70% of global water withdrawals—versus water for nature. Less than one percent of Colorado River water reaches the ocean and the Yellow River in China runs dry up to 60 days a year. A recent study suggests that allocating water to maintain Environmental Reserve Flows (ERF) in all global rivers would decrease the total irrigation water supply by 18% (Strzepek *et al*., 2013).

A key issue facing the global water resource community is urbanization, which poses at least three challenges. First, urban residents demand three to five times more water per capita per day than rural residents, driving up regional domestic water consumption. Second, most urbanization occurs near the coast. With urban uses (domestic, industry, manufacturing, services) commanding a much higher price on water than rural uses, more and more water gets diverted from fertile crop lands to cities, and more polluted return flows are discharged to coastal waterways and estuaries. Finally, due to demands for fresh foods for the urban market, agricultural development in areas surrounding metro urban regions is rapidly growing. Much of this cropland is irrigated, some with the municipal water supply, leading to water quality issues and pressure on the urban water supply and wastewater system.

There are some promising approaches to help reduce the likelihood of water shortages due to urbanization, climate change and other factors described above. For example, to limit physical resource scarcity, municipalities and businesses could deploy demand management systems that more efficiently distribute water, and the agriculture sector could improve the efficiency of irrigation technology and cultivate drought-tolerant crops. To address economic resource scarcity, public/private partnerships and new financing options could be established to improve the water infrastructure. And to reduce water-use conflicts, thermal power stations could use water recycling technology and wind/solar/hydropower networks—in which the hydro component functions as a "battery" to store electrical energy—could be developed.

Dr. Kenneth Strzepek is a research scientist and water resource expert at the MIT Joint Program on the Science and Policy of Global Change.

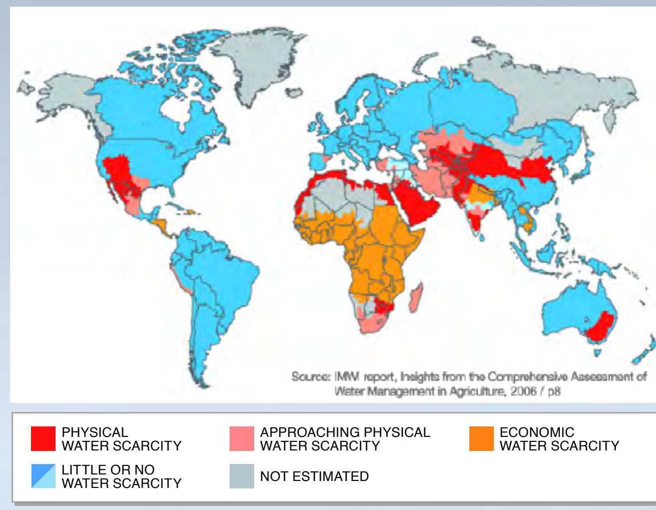
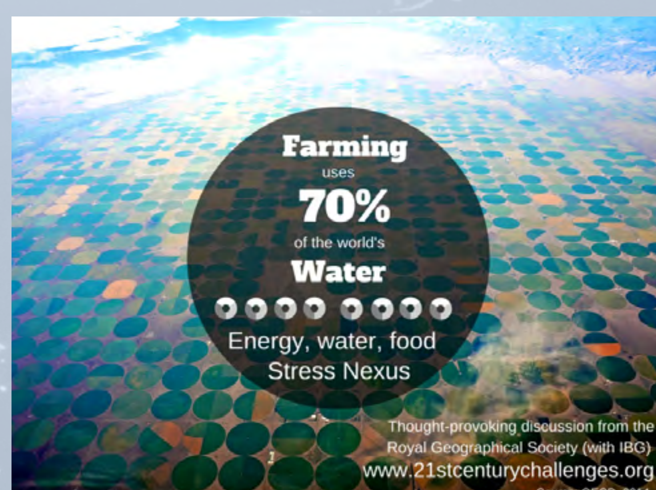


Figure 24. Current Global Water Scarcity



2°C Stabilization Scenarios & the Technologies to Achieve Them

In 2010, the Cancun meeting of the Conference of the Parties to the Framework Convention on Climate Change identified 2°C as a dangerous threshold for climate change that should not be exceeded. In 2016, the Paris agreement went beyond that by calling for "aggregate emission pathways consistent with holding the increase in the global average temperature to well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5°C." (For a brief history of how the world came to this target and various issues that arise in defining emissions pathways consistent with a temperature target, see **Box 8**.)

Emissions Paths and 2°C

In calculations presented here, we have used the MIT IGSM to calculate stabilization paths consistent with 2°C. Other approaches and model formulations would generate different stabilizations paths, but in all cases eventually emissions must be very low. Toward that end, the IGSM comprehensively treats emissions of gases, and abates them, with explicit atmospheric chemistry to calculate concentrations of all gases, their time-dependent oxidation or uptake and time-dependent temperature implications, with uptake of carbon by land and uptake of carbon and heat by the ocean. We calculate concentration pathways for a median, high and low Earth-system response explicitly rather than using simplified approximations of a carbon budget or exogenous assumptions about the contribution of other sources. While the IPCC uses fairly precise language, where "likely" staying below 2°C means a 67% chance given characterization of uncertain Earth-system response to GHG forcing, the language in international agreements (e.g., Cancun and Paris) is less clear, and different parties to the agreement no doubt have different interpretations of "holding the increase in the global average temperature to well below 2°C above preindustrial levels."

We develop three emissions scenarios consistent with stabilization at 2°C for median, low (fifth percentile) and high (95th percentile) climate sensitivity, choosing values of ocean heat uptake and aerosol forcing to replicate historical climate. We show CO_2 emissions along with CO_2 equivalent emissions for each scenario (**Figure 25**). As in the *COP21 Outlook* scenario, we also use a single central value for ocean heat uptake and ad-

Box 8.

The 2°C Challenge

The 2010 Cancun agreement, which sought to "hold the increase in global average temperature below 2°C above pre-industrial levels," marked the first time the target was included in a broad international agreement. However, scientific and policy discussion of the target goes back to 1990 or earlier. Scientific discussion first formally identified 2°C as an aim in a 1990 report of the Stockholm Institute, *Targets and Indicators of Climate Change*. The report concluded that "temperature increases beyond 1.0°C may elicit rapid, unpredictable and non-linear responses that could lead to extensive ecosystem damage." It suggested targets of 1.0°C or 2.0°C, with the latter accepting greater risk. The report also suggested a target of warming of no more than 0.1°C per decade, recognizing that rapid change presented greater challenges for adaptation. The European Council of environment ministers is generally credited as being the first political body to support the target, with a 1996 declaration to that effect. The 1992 UN Framework Convention on Climate Change set a goal to stabilize "greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system," but did not define "dangerous." The Intergovernmental Panel on Climate Change took up the task of considering what was dangerous over a series of meetings and reports. Working Group III's 2007 report directly addressed the question, arguing that defining dangerous interference was a "complex task that can only be partially supported by science, as it inherently involves normative judgements." It went on to review a variety of "principally scientific (expert-led) assessments" that identified the 2°C target, with one assessment concluding such an increase to be 'an upper limit beyond which the risks of grave damage to ecosystems, and of non-linear responses, are expected to increase rapidly.' The IPCC also noted the EU Council's 2005 agreement to avoid exceeding 2°C. The Paris agreement intensified the challenge by repeating the goal of achieving "aggregate emission pathways consistent with holding the increase in the global average temperature to ***well below*** 2°C above preindustrial levels" (emphasis added) and adding the goal of "pursuing efforts to limit the temperature increase to 1.5°C."

There are multiple issues that arise when we ask the simple question: Are we on a 2°C path?

First, policy can target emissions of greenhouse gases, and so one must have a translation of emissions into temperature. The IPCC introduced the idea of a carbon budget, on the simplifying assumption that warming is approximately linearly related to the amount of CO_2 in the atmosphere. This makes it an easy calculation to ask: How many years would it take to spend the entire budget, or to plot a gradual decline in emissions while staying within that level of cumulative emissions?

Second, there is uncertainty in relating the emissions to temperature. Lowering further the cumulative emissions from the central budget estimate will improve the chance of staying within the 2°C target, given uncertainty in Earth-system response to GHG forcing. The IPCC determined a budget that would "likely" keep temperature below 2°C, and in their terminology, "likely" means greater than a 67% chance of staying below that level.

Third, other greenhouse gases and forcings contribute to warming (and cooling), and so some calculation of that contribution is needed. Based on 2°C scenarios, the IPCC estimated 0.4°C of net warming from other sources, meaning CO_2 could only contribute 1.6°C. The end result is an estimated carbon budget of 800 million metric tons (mmt) of CO_2, of which 531 mmt have already been emitted through 2011. The world has been emitting at about 35 mmt per year, and so by the end of 2016 we will have spent another 175 mmt, for a total of 706 mmt already spent. That leaves just 94 mmt unspent, less than 3 years at current emissions rates.

Fourth, the absolute budget is an approximation. If the world were to reduce emissions to zero (at the end of 3 years), the concentrations in the atmosphere and ocean would be out of balance and would remain so for thousands of years. This means the ocean would continue as a net sink of carbon, and atmospheric concentrations would continue to drift down. Another way to look at this is that we could continue to emit some amount of carbon for many centuries while keeping atmospheric concentrations stabilized because of the slow mixing of the ocean.

Fifth, other GHG sources may be different than from that assumed in the IPCC calculations, and forest regrowth could take up carbon, possibly giving more room for CO_2 emissions from energy and industrial sources.

Sixth, what the long-term goal means for the next five or 10 years depends on the path of abatement over the longer-term. Assuming steeper cuts in the future allows more headroom in the near-term. Many of the IPCC scenarios included biomass energy with CCS, which creates a negative emissions technology. That, combined with the continued uptake by the ocean (of CO_2 and heat), means that concentrations levels can overshoot the long-run stabilization goal consistent with an equilibrium temperature increase of 2°C and still not exceed the temperature target. Also, given the short lifetime of methane, significant reductions in emissions can lead to fairly quick drops in concentrations, providing more short-term room for CO_2 emissions. As a result, there is not a single answer to the question: ***Is our current path consistent with a 2°C target?***

just aerosol forcing in the high and low climate sensitivity cases to ensure that simulations match the historical climate record.

The paths with fewer emissions (*2CH* and *2C*) give a great likelihood of keeping the rise in global mean surface average temperature (SAT) since preindustrial times below 2°C. The *2C* emissions path (median climate response) gives about a 50–50 chance of keeping the SAT below 2°C. The *2CH* emissions path (high climate response) increases the chance of keeping the SAT below 2°C. Of course the *2CL* emissions path (low climate response) increases the chance of exceeding 2°C. In **Figure 26** we take the *2C* and *2CH* emissions paths, assume a median climate response for both, and simulate SAT. As one would expect, the climate simulations exhibit variability, but the climate appears to have approximately stabilized in 2060 or 2070 onward, at 2°C for the *2C* emissions path (as constructed), and at around 1.7°–1.9°C for the *2CH* emissions path.

As illustrated, the concept of temperature stabilization must be considered by averaging temperature over a longer period of time (two to three decades or more) because with natural variability, mean surface temperatures can vary by 0.2 to 0.3°C from year to year or decade to decade. Also, consistency with any temperature target over the longer run depends on what happens to emissions over that period. Given the different lifetimes and radiative effects of different gases, exactly how temperature stabilization relates to multiple greenhouse gases is a complex question. In principle, if net emissions of methane from livestock and rice and nitrous oxide from fertilizer use are difficult to force to zero, these could be offset by net removals of CO_2, but the exact level of CO_2 removal over time would be a complex calculation.

Our 2°C scenarios are constructed assuming the world continues on the Paris agreement path through 2025, and then begins a concerted global effort of carbon pricing to get on an emissions path consistent with 2°C given the different climate system responses (*2CL*, *2C* and *2CH*) assumed. If the Paris agreement were on a path consistent with stabilization, then we would expect to see a very smooth transition between 2025 and 2030. In all three cases (Figure 25), however, there is a jump down in the emissions path in 2030 from 2025, indicating that the Paris agreement is not as aggressive as needed, at least as we model the cost of options to abate emissions over time. The five-year transition requires a drop of 6 million tons (mt) of CO_2 (8 mt CO_2-e) for low climate sensitivity, 13 mt CO_2 (17 mt CO_2-e) for median climate sensitivity, and 21 mt CO_2 (23 mt CO_2-e) for high climate sensitivity. The median case is a reduction of emissions of about 31% in five years; the high sensitivity case cuts emissions in half in five years. Given the goal of "well below" 2°C or even 1.5°C, we almost certainly need to shoot for the *2CH* emissions path. Hence the charge for negotiators for the next round of discussions is to set in place targets that would cut global emissions by 50% or more by 2030 from the 2025 level.

As noted earlier, what needs to be done in the near term depends on what is possible in the longer term. We have not included an option of biomass energy with CCS, which could allow emissions to go toward zero or below over the longer term. Even if we could get to negative CO_2 emissions from energy, eliminating all of CO_2 emissions from cement and steel production, all methane emissions from livestock and rice production, and all nitrous oxide emissions from fertilizers, or doing completely without these commodities seems nearly impossible. Thus, negative emissions somewhere would be needed just to get to zero net emissions. The possibility of zero or net negative emissions in the longer term would provide room for a more gradual transition. The ways out of the apparent inconsistency of Paris with 2°C are much more optimistic zero and negative-emitting technologies, and an assessment of climate response that is different from what we estimate is likely.

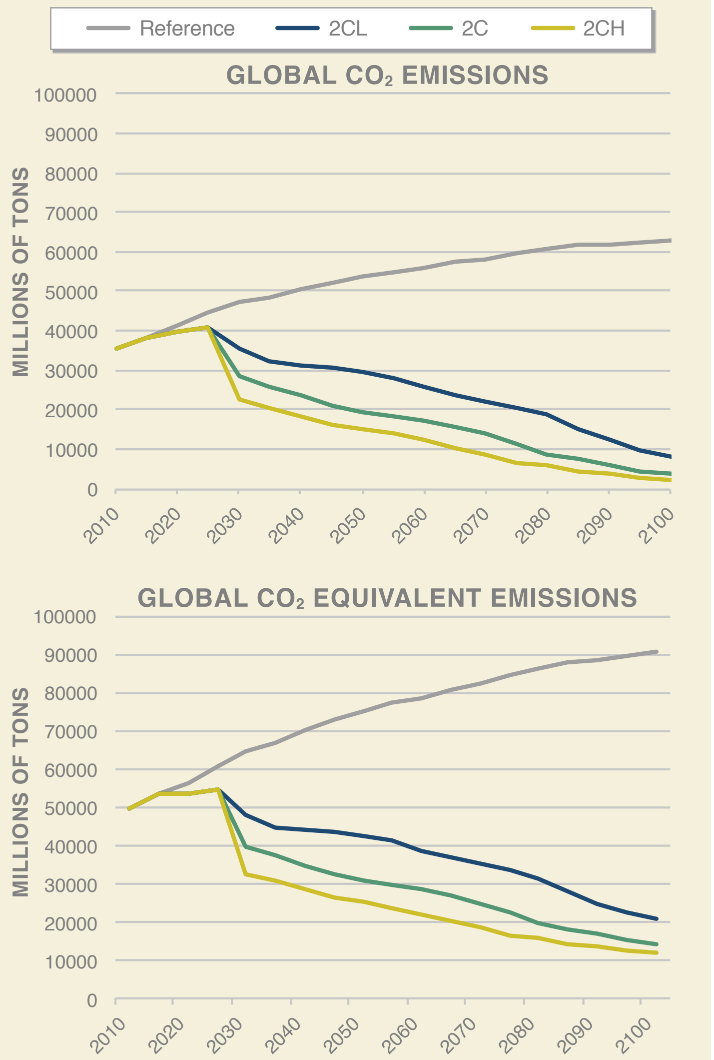


Figure 25. 2°C Emissions Paths for Low (*2CL*), High (*2CH*) and Median (*2C*) Climate Response

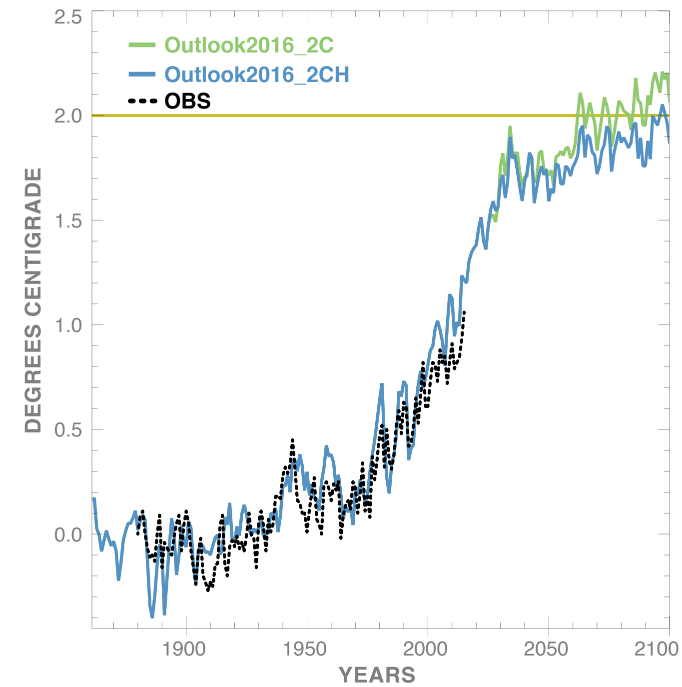


Figure 26. Mean Surface Average Temperature (SAT) for the *2C* and *2CH* Emissions Paths with median climate response

Energy Technology Paths and Research Challenges

Clearly, the energy sector would need to undergo a complete transformation from its current structure (or that we project for 2025 given the Paris agreement) fairly rapidly to meet any of the emissions paths sketched out in Figure 25. As indicated in our *COP21 Outlook* scenario, fossil energy currently contributes about 86% of the world's energy. This would fall slightly under the Paris agreement, to about 83% by 2025, and remain at about 75% in 2050 and 70% in 2100. Under the 2°C case with median climate response and median assumptions about the costs of technologies, fossil's share of global energy falls to 38% by 2050 and 3% by 2100 (**Figure 27** in **Box 11**).

In this section, some of our researchers, along with guest experts, explore how an energy system capable of producing such targets might be achieved. In the following six perspectives on the future of nuclear, bioenergy, solar, electric power storage, electric power grid and carbon capture and storage technologies, they describe barriers to commercializing these key energy technologies and systems, and the hoped-for technological breakthroughs that could make them technically and economically viable.

Advanced Nuclear Reactors

By Irfan Ali & Samuel Thernstrom

A number of new and existing companies are engaged in the development and commercialization of advanced (Generation IV)

Box 9.

Modeling Limits on the Speed of the Energy Transformation

There are many arguments in the literature and in discussions about how fast the world's energy system can change. A popular argument is that we are stuck with long-lived capital, and that limits the speed at which we can change emissions. This argument is based on the stylized fact that large capital investments (e.g., coal power plants) have a natural lifetime after which they wear out, and so they will continue to produce power at full capacity for their lifetime. In fact, this characterization has little to do with reality. Lifetimes of long-lived capital investments are generally assumed to be on the order of 30 years, yet more than half of the power plants in the U.S. are more than 50 years old. When economics are right, lifetimes can be extended; similarly, if economics change in the other direction, power plants may be retired early. At one point, it appeared that many nuclear power plants in the U.S. might seek relicensing to operate beyond their original license. However, a combination of low natural gas prices and further safety requirements post-Fukushima have resulted in many getting slated for decommissioning. Power plants also operate in most places on a merit order that dispatches the least-cost operators first/most of the time, and brings in higher-cost operators when electricity demand is higher. Hence, while older, more inefficient plants may remain in service, economics may dictate that they operate at lower capacity factors. Hence, the "lifetime" of capital depends on economic conditions, and at least for the electricity sector, intermediate stages of less-than-full capacity operation are possible and actually the norm.

Carbon pricing would significantly change the merit order, thereby altering the actual capacity factor of different technologies and potentially forcing early retirement. In terms of our scenarios, if the goal of 2°C appeared to be a credible political commitment that would require the steep emissions reductions we estimate, then investors would look forward and likely reduce investment in CO_2 emitting capital stock beginning immediately. This would smooth out the transition between 2025 and 2030 by exceeding initial goals set by the Paris agreement. The failure of countries to commit to tougher emissions reductions in the short term essentially undermines the credibility of the long-term commitment. Of course, there is still time to convince countries to accelerate their reductions prior to 2025 because it will reduce costs after 2025.

Another argument suggesting a built-in speed limit on a global energy transformation is that financial resources for the needed investment may be unavailable. In our modeling of energy choices, we include limits on savings and investment, and so the argument that capital resources are insufficient to make a rapid transition is addressed. Rapid scale-up means drawing investment away from other sectors, pushing up the cost of capital. We also address endogenous and partial retirement by specifying capital lifetimes, but allow partial or total early retirement if economics dictate. The price path we solve for that is necessary to meet the 2°C target given global mitigation efforts up to 2025 optimally spreads costs over the full horizon of our model. So a rapid adjustment, which might seem implausible, actually is "optimal," at least in an economic sense, given the new information that we are suddenly on the wrong path and must make a course correction. This adjustment would likely create stranded assets, but at that point they are sunk costs that cannot be recovered, and so they should not affect our decisions going forward. However, they do indirectly come into play in the carbon price. Given that there is sunk investment, assets can continue to operate as long as prices cover just the variable costs, and as demand for fossil fuels drop off, these prices tend to fall. So the existence of sunk investments in fossil technology can allow fossil fuel use to persist longer, or requires a higher carbon price so that the variable fuel and carbon costs alone make these technologies uneconomical to operate. In our modeling, we also include adjustment costs for rapidly scaling up new energy technologies. Adjustment costs, sunk costs and capital crowding all increase the cost of rapidly changing course. Hence the carbon price and overall economic cost required to make that change is that much higher than if all capital could be reinvested or retrofitted without cost, there was no large new call on financial investments, and new industries could be scaled up without waste and limit.

As we model these things, none are absolute constraints, and all add to the cost and carbon price that is endogenously determined as needed to meet the carbon budget associated with 2°C. That said, while we have included some representation of these phenomena, they are at best an approximation. We also assume that the public and policymakers suddenly see and agree that this drastic change in direction is needed, put in place the necessary measures, and are willing to bear the adjustment costs.

Box 10.

Energy Technologies and the 2°C Challenge

What the energy transformation will look like depends on the relative (and absolute) costs of different technologies, which remain uncertain and depend on the level of R&D spending among other factors. There are also many issues regarding how fast this transformation can occur. To illustrate a few of these possibilities, we have chosen different relative prices of technology options based on cost estimates developed by the International Energy Agency (IEA/NEA, 2015). The IEA minimum, median and maximum cost inputs are used to generate low, base and high technology costs, respectively, for each technology. From these scenarios, we have selected a few so as to demonstrate different technology transformations that would be consistent with the 2°C goal, conditional on all the other characterizations of abatement options we have represented in the model. The various technology cost scenarios change the needed course correction between 2025 and 2030 from the emissions paths shown in **Figure 25** somewhat, and therefore the initial carbon price, but not substantially.

reactors. These designs incorporate a diverse set of technologies that could have profound effects on the economic competitiveness of nuclear power, as well as other core issues for the industry such as safety, waste generation and proliferation resistance. Perhaps most importantly, small modular reactors (SMRs) are intended to provide electrical power in a reduced form factor and distributed architecture, enabling more rapid penetration in a range of markets. These reactors have several features that give them significant advantages over traditional light water reactors (LWRs).

SMRs allow for factory production and quicker field installation (approximately 24 months vs. 5–7 years). These reactors will be small enough that their modularized components can be shipped and installed onsite using regular commercial equipment, such as barges, rail, trucks and construction cranes. The customer can begin generating cash flow much sooner, and install additional power-generating capacity in more manageable increments. Preliminary cost estimates indicate that, with factory based large-scale manufacturing, some of these designs can be produced and installed on a turnkey basis at a customer's site at a projected cost of under $3,000 per kilowatt—making them potentially very competitive with other sources of electrical power.

In some of these designs, the use of sodium instead of water as the heat-transfer agent in the reactor allows the reactor to operate at ambient pressure. Sodium is a liquid at the reactor operating range of 350–550°C, and therefore does not have to be pressurized to prevent boiling and conversion to a gaseous state. (Sodium melts at 98°C and boils at 883°C.) Water boils at 100°C at ambient pressure, and thus must be highly pressurized to remain in a liquid state at the operating temperatures in a reactor. Consequently, LWR reactor cores must be contained in forged steel vessels that are expensive to manufacture, and today only a few factories in the world are capable of creating such vessels for large LWRs. The reactor cores for some of the advanced designs are contained in a double-walled stainless steel tank that can be made in nearly any steel fabrication shop. Additionally, some of these reactors use a "pool" design that is simpler to build and operate than liquid metal fast reactors using a "loop" design.

Sodium is reactive with many other elements and thus must be kept properly contained and isolated from air and moisture. These reactors achieve this by maintaining a layer of argon gas above the sodium pool in the reactor chamber. Argon is heavier than air; so it remains in place and separates the sodium from any outside air that might penetrate the chamber.

Another advantage offered by some of these advanced designs is that their passive safety feature is failsafe and does not depend on extra pumps or any external systems. For instance, in response to an accident such as loss of coolant flow, or loss of the ability to reject heat from the reactor system, the reactor safely stabilizes its internal operating temperature without human or safety-system intervention. Subsequently, the reactor can be returned to service as soon as the problem has been addressed.

Box 11.

Nuclear and the 2°C Challenge

Figures 27 and 28 show global primary energy and electricity generation under a 2°C scenario with base (median) assumptions about the costs of all technologies (as well as median climate response). Under these assumptions, nuclear energy becomes the dominate source of electricity across the globe. While such a rapid expansion of nuclear may seem unattainable, in fact we have seen such rapid expansion in the U.S. in the 1970–80s as well as France in the 1980–90s. Of course, to reach this level globally, nuclear would need to overcome the many challenges addressed above. Even if the basic economics and technological issues around safety and proliferation with nuclear are resolved, society-at-large would likely need to be convinced that nuclear was a safe option, enabling streamlining of regulations for approving, siting and constructing "next generation" technology.

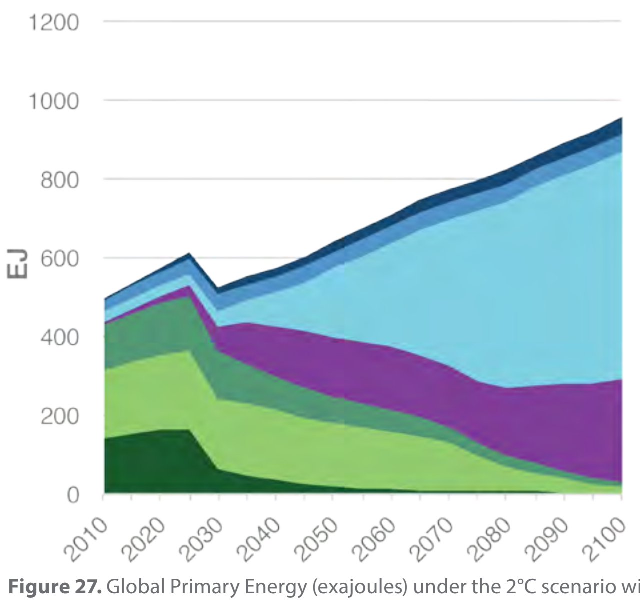


Figure 27. Global Primary Energy (exajoules) under the 2°C scenario with median assumptions about technology costs & median climate response

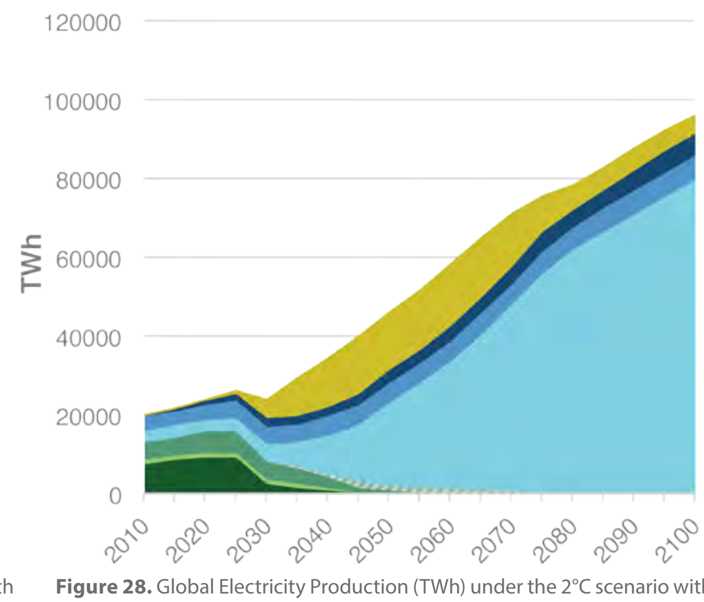


Figure 28. Global Electricity Production (TWh) under the 2°C scenario with median assumptions about technology costs & median climate response

This capability arises in large part from the use of metallic fuel (a uranium-zirconium metal alloy) instead of the uranium oxide that is currently used in most fuel rods worldwide. Due to less rigid binding of atoms in the molecules, metallic fuel expands and contracts much more than an oxide fuel when it is heated or cooled; this thermal expansion in metallic fuel is what provides the reactor with true passive safety. The heat-related expansion increases the distance between atoms as the temperature rises, resulting in neutron leakage. In the event of an abnormal rise in core temperature above an acceptable threshold, the immediate loss in neutrons stabilizes the temperature well below the failure level of either the fuel rods or the reactor core. Therefore, even if an accident causes a failure in the pump that moves the fluid in the reactor core, such reactors do not experience a meltdown, or even damage to the reactor core.

The operational characteristics of a fast neutron spectrum reactor offer fundamentally new solutions to the problem of nuclear waste. Viable fuel sources for such reactors could include:

- The so-called waste created by LWRs (which still contains about 95–97% of its energy potential unfissioned);
- The large, existing, global stockpiles of depleted U238; or
- The nuclear materials removed from nuclear weapons, which create a serious storage and security problem.

Creating fuel for such a reactor from nuclear waste does not involve separating pure plutonium that might be suitable for direct use in nuclear weapons, as is the case with conventional reprocessing technology; instead, the pyro-processing technique used in this case would keep the plutonium mixed with other long-lived radioisotopes in a form factor completely unsuited for weapons design.

These advanced reactors thus offer a new approach to dealing with nuclear waste, in effect acting as a nuclear waste incinerator. The ability of these reactors to recycle nuclear waste will generate additional energy, consume the plutonium that could be used for weapons, and eliminate the need to bury or store large quantities of nuclear waste. It could enable a new worldwide standard that would revolutionize nuclear fuel cycles and the eventual storage of nuclear waste materials. The fast reactor spectrum allows the "burning" of transuranic elements in nuclear waste (the components of waste that have very long isotopic lives and high levels of radio toxicity) to generate more useful power; this would greatly reduce the volume of waste and the time scale for monitored storage of the remaining waste. The vast majority of any waste products from such reactors will be the much shorter-lived fission products, the required storage times for which are measured in hundreds of years rather than "a million years" (the criterion of record for the Yucca Mountain Repository).

The reactor cores for a number of Generation IV designs are intended to operate for an extended period (20–30 years) without refueling. At the end of this period, new fuel is delivered and installed. The old fuel is returned, intact and sealed, to a pre-determined location where it is recycled and refueled with both new U238 and fuel elements recovered from the old fuel. This re-use of old fuel is possible because these reactors are "breeding" in their cores approximately as much new fuel as they use by converting U238 into usable fuel.

The extended refueling cycle means there is no need to have new fuel rods installed in the reactor every 18–24 months, as is the case with the current generation of reactors. This, in turn, means that:

- The reactor is cheaper to manufacture because there is no need to include fuel handling equipment in the reactor structure;
- Staffing is cheaper because the staff does not require sophisticated refueling skills;
- Spent fuel is never stored on the reactor site in cooling ponds;
- There is less opportunity for the enriched uranium in new fuel rods to be stolen during shipping, storage or refueling; and
- Significantly more competitive economics since all subsequent reactor cores, after the initial one, can be fabricated at a fraction of the original cost.

Generation IV SMRs represent a unique opportunity for a long-term, sustainable solution for clean energy. While there are a number of clean energy options, nuclear is unique in its ability to provide large-scale, stable supplies of baseload and dispatchable energy. SMRs offer a potentially unique value proposition in the nuclear energy market by creating the possibility of a fully distributed power generation architecture that does not require an extensive electrical grid. At the same time, the relatively simple deployment of SMRs leads to a more efficient utilization of capital through a much shorter time-to-market.

Irfan Ali is a member of the board of directors of Advanced Reactor Concepts, and managing director of the Energy Information Reform Project (EIRP), a nonprofit organization that promotes the development of advanced energy technologies and practice. Samuel Thernstrom is executive director of the EIRP and a senior fellow at the Center for the National Interest.

Bioenergy

By Niven Winchester & James Primrose

Biomass can provide a low-carbon alternative to fossil fuels, in both liquid and solid forms for direct heat or for the production of electricity. The cultivation of biomass crops has raised concerns about food prices and deforestation, and there remain technical issues in producing a fuel that is competitive with gasoline, diesel and jet fuel. With sufficient economic incentives, global primary bioenergy equivalent to that currently derived from oil, gas or coal appears achievable by 2050 at small-to-modest increases in food prices. With protection of forests, and incentives for CO_2 sequestration, it appears possible to avoid deforestation, and even increase land carbon storage, according to recent work (Winchester and Reilly, 2015)

At current costs, biomass used for heat and electricity and some first-generation biofuels—mainly sugarcane ethanol in Brazil and corn ethanol in the U.S.—can compete with conventional energy with little or no policy incentives in some markets. Much effort has been directed toward advanced biofuels, which can convert a wider variety of plant material to liquid fuel, increasing the energy yield per hectare of land, and making use of land that competes less directly with food crops. Biofuels are one of few options to lower carbon dioxide (CO_2) emissions from aviation, but mitigation costs from aviation biofuels, given current conversion technology, are estimated to exceed $250 per ton of CO_2 abated.

Broader commercial viability of these fuels depend on advances that lower costs and reduce barriers to using the fuel.

One pathway to second-generation fuels is through enzymatic conversion of the lignin and cellulose material in plants to starches and sugars, allowing conventional fermentation to ethanol. The key breakthrough needed here is improved enzymes that can rapidly break down lignocellulosic material, allowing rapid throughput and thus lowering capital costs. Second-generation ethanol faces the same blend-wall and associated issues as corn and sugarcane ethanol. To remedy these concerns, techniques for further conversion of the fuel to butanol or so-called drop-in fuels that have the same properties as gasoline or diesel are being investigated. These pathways produce higher-value fuels, but also involve more complex conversion processes with lower energy yields and hence higher costs.

Another pathway is conversion of biomass to drop-in fuels via thermochemical conversion, such as Fischer-Tropsch and gasification processes. As these processes are highly capital-intensive, large-scale production is needed to minimize costs, which presents challenges for deployment of these technologies. Additionally, although they have yet to be deployed to biofuel production, these processes are mature technologies, so there is little prospect for significant further technical advances that will reduce costs.

Box 12.

Bioenergy and the 2°C Challenge

Figures 29 and 30 show global primary energy and electricity generation under a 2°C scenario in which bioenergy dominates over other technologies. Specifically, all technologies are assumed to be at their base (median) costs (including bioenergy), but nuclear is assumed to be high cost. When nuclear is expensive or unavailable or constrained, bioenergy and bioelectricity can be the dominant global energy source, replacing oil products for transportation and providing more than half of global electricity.

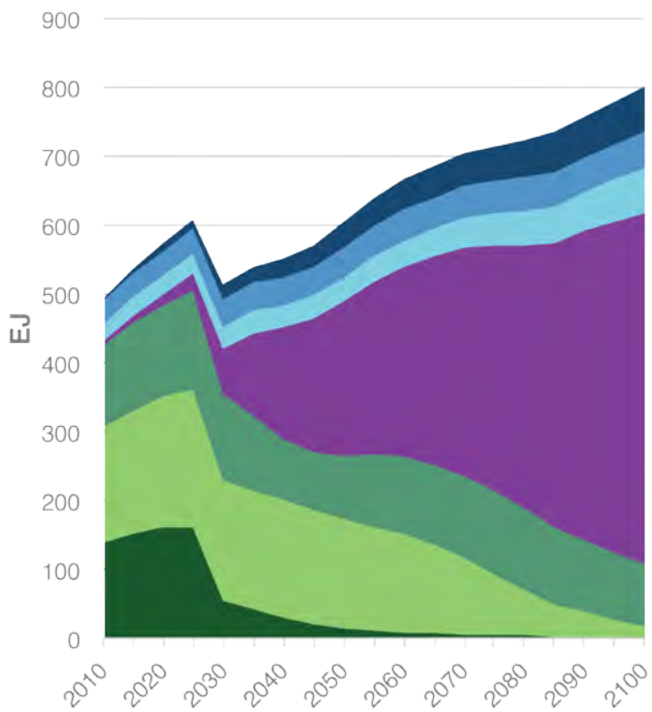


Figure 29. Global Primary Energy (exajoules) under the 2°C scenario with high nuclear costs and median climate response

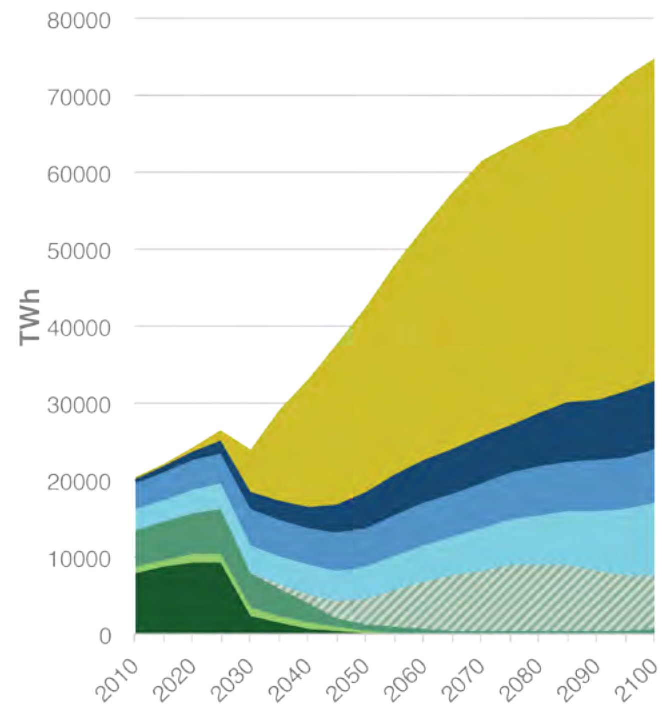


Figure 30. Global Electricity Production (TWh) under the 2°C scenario with high nuclear costs and median climate response

Even when deployed at large scale, these fuels may have difficulty achieving costs that can compete with conventional petroleum products if crude oil prices remain below $150 per barrel, and lacking other incentives such as carbon pricing.

Adding carbon capture and storage (CCS) to biomass-generated electricity could lead to a technology with negative emissions, with growing biomass crops scrubbing CO_2 from the atmosphere. Key obstacles for this technology include low energy-conversion efficiency, high CCS costs, CO_2 storage-capacity uncertainties and limitations, and social acceptance of CO_2 storage.

In summary, a variety of biomass energy technologies could contribute to abatement of CO_2 emissions, but would likely require major cost-reducing breakthroughs or carbon pricing on fossil competitors.

Niven Winchester is a principal research scientist at the MIT Joint Program on the Science and Policy of Global Change.

Solar

By Patrick Brown & Francis O'Sullivan

The solar resource is larger and more evenly distributed than any other terrestrial energy resource. While solar power has historically been one of the most expensive energy technologies, solar electricity has been declining in cost for decades and, within the past few years, has begun to reach economic competitiveness with other grid-scale electricity sources in certain locations with superior insolation, including regions of the U.S. Southwest and southern Europe.

Grid-connected solar-electric power can be divided into two classes: concentrating solar thermal power (CSP) and photovoltaics (PV). CSP uses concentrated sunlight to heat a working fluid and operate a turbine, while PV converts sunlight directly into electricity in a solid-state PV module with no moving parts. Solar PV accounts for ~98% of installed solar generation capacity worldwide, so we here focus on PV (REN21, 2016).

Solar PV can be divided into three technological classes: commercial wafer, commercial thin-film and emerging thin-film. Commercial wafer-based PV, typified by crystalline silicon (c-Si, both monocrystalline and polycrystalline), currently dominates the PV market—roughly 92% of PV module shipments in 2014, including the vast majority of rooftop PV modules, employed crystalline silicon solar cells (Mints, 2015). Crystalline silicon is the highest-efficiency PV technology deployed at grid-scale today, with record-certified cell efficiencies of 25% and large-area module efficiencies of up to 22% for monocrystalline silicon for certain suppliers (NREL, 2015; SunPower, 2014). Crystalline silicon PV also demonstrates high performance stability and lifetime, and is primarily manufactured from highly abundant materials. These modules have fallen in cost from ~$3.50/W in 2008 to ~$0.65/W in 2015 (ITRPV, 2015), and utility-scale balance-of-system (non-module) costs in the U.S. have fallen from ~$2.50/W in 2008 to ~$1.10/W in 2015 (Bolinger and Seel, 2015; Chung *et al.*, 2015).

Commercial thin-film PV includes cadmium telluride (CdTe, 5% of module shipments in 2014), copper indium gallium diselenide (CIGS, 2% of 2014 shipments) and amorphous silicon (a-Si, <1% of 2014 shipments) (Mints, 2015). CdTe in particular is competitive with c-Si PV in utility-scale installations due to its low module cost per watt enabled by high-throughput production methods, as well as its simplified installation methods. CIGS is compatible with flexible modules for rapid deployment of off-grid systems, but has not seen wide application for grid-scale power production. The dependence of CdTe and CIGS on rare metals (tellurium for CdTe and indium, gallium, and selenium for CIGS) that are primarily produced as byproducts of more common metals, while not currently limiting at the present scale of deployment, could present serious difficulties in scaling these technologies to the terawatt level.

Emerging thin-film PV encompasses a range of technologies that have yet to be employed for grid-scale power production, but have been the focus of significant research efforts over the last two decades and could lead to flexible, low-weight, low-cost PV options in the future. Organic, quantum-dot and dye-sensitized solar cells have demonstrated certified single-cell efficiencies of 11–12% (NREL, 2015), but module efficiencies, if demonstrated, are typically much lower. Organic and dye-sensitized solar cells have been commercialized for niche applications, such as semi-transparent windows, but are currently too expensive for grid-scale deployment. Perovskite solar cells, a relative newcomer to the field, have undergone explosive growth in efficiency, rising from 3.8% efficiency in 2009 to 22.1% efficiency today (NREL, 2015; Kojima *et al.*, 2009), roughly equal to certified cell efficiencies for CdTe and CIGS and higher than cell efficiencies for multicrystalline silicon. Module-scale perovskite devices have yet to be demonstrated, however, and challenges remain for the manufacturability, stability and lifetime of this technology.

Patrick Brown is a U.S. Department of Energy Postdoctoral Fellow. Francis O'Sullivan is the director of research for the MIT Energy Initiative, and a senior lecturer at the MIT Sloan School of Management.

Electric Power Storage

By Apurba Sakti & Francis O'Sullivan

Energy storage systems (ESS) will play an important role in enabling the transition to lower-carbon energy systems for both electric power and transportation. Demand for ESS in the nascent electricity grid market grew by 243% (221MW, 161MWh) in 2015 (Energy Storage Association, 2016). This represented the largest annual deployment on record, and grid-level ESS installation levels are forecast to grow significantly over the coming years due to these systems' ability to facilitate the integration of large-scale non-dispatchable renewable energy sources, including solar PV and wind. Beyond renewables integration, there is expected to be increased reliance on ESS assets for managing growing transmission and distribution (T&D) needs and for providing increased system capacity. The already appreciable demand for storage technologies from the transportation sector also continues to see very strong growth. The market for electric vehicle (EV) lithium-ion batteries amounted to ~11 GWh in 2015 (Chung *et al.*, 2016), and this is expected to expand to over 50 GWh by 2020, as the penetration of electrified vehicles accelerates and the size of the typical onboard battery increases.

Lithium-ion batteries, with their higher energy densities, have become the market leader for the more space-constrained applications typical of the transportation sector. However, for the many grid-level applications that exist, a range of energy storage options exists. Today's grid-level ESS technology options can broadly be divided into four categories: 1) mechanical (pumped hydro, compressed air energy storage, and flywheels), 2) chemical/electro-chemical (batteries and electro-chemical capacitors), 3) magnetic (superconducting magnets) and 4) thermal (molten salt). These storage technologies all vary in their technical and economic performance characteristics, and in terms of their technological and market maturity.

Flywheels are better suited for applications that require high power and fast response times, like uninterruptible power supply, but are not very suitable for bulk energy storage applications, where options like pumped hydro or compressed air are more cost-competitive. Pumped hydro energy storage (PHES) comprises ~97.5% of the global energy storage capacity (DOE, 2016), but suffers from limitations arising from geographical settings, licensing and environmental regulations. Compressed air systems account for ~1% of the global installed capacity, but these plants often have lower than desirable roundtrip efficiencies (e.g., 27% for the McIntosh plant (EPRI, 1994)).

Rechargeable batteries, which can be sized and sited without geographical constraints, have attracted significant contemporary research and commercial interest. Of the numerous battery chemistries and configurations, lithium-ion, sodium sulfur and

lead-acid are considered mature, while technologies such as aqueous sodium ion, advanced lead-carbon, hybrid zinc-air and flow batteries are still in the demonstration phase. Additionally, lithium-sulfur, liquid metal, and semi-solid flow are at various R&D stages and may eventually provide lower-cost alternatives to existing technologies. Recent breakthroughs on semi-solid lithium ion batteries may disrupt the incumbent lithium ion technology if they manage to slash manufacturing costs by 50%, in addition to removing more than 80% of the inactive components. This will go a long way in meeting the Department of Energy's (DOE's) Advanced Research Projects Agency-Energy's (ARPA-E's) capital cost target of $100 per kWh for 1 hour of storage for widespread adoption (DOE, 2010). At present, lithium-ion batteries cost ~$300 per kWh at the pack level for larger battery packs (>20 kWh) (Sakti *et al.*, 2015; Nykvist & Nilsson, 2015).

The opportunities and challenges associated with the large-scale integration of renewables, the evolution toward a more distributed power system, and the associated storage technology and policy needs are complex and nuanced. However, if several key needs are addressed, it would aid in expanding storage service availability.[1] At the grid level, three aspects of regulation, policymaking and market design need to be addressed (Pérez-Arriaga, 2015): 1) the definition of storage and whether it should be categorized as a generation or demand asset; 2) designing the market for all timeframes: long-term capacity, day-ahead and ancillary services; and 3) grid tariffs based on the principle of cost causality. There is also a need for power-system specialists and storage-technology specialists to work together to guide and align the technical and economic development of storage technologies with the needs in the field. Finally, continuing and expanding public support for basic and applied research focused on developing better-performing and more cost-efficient technical options is needed. However, in terms of deployment support, policies that try to pick winners should be avoided, and market-based mechanisms should be used to encourage and support the deployment of the optimal techno-economic storage solution for any given application.

Apurba Sakti is a Research Scientist at the MIT Energy Initiative. Francis O'Sullivan is director of research for the MIT Energy Initiative, and a senior lecturer at the MIT Sloan School of Management.

1 For more on this, see Sakti and O'Sullivan (2016).

Electric Power Grid

By Nidhi Santen & Francis O'Sullivan

Addressing climate change requires widespread changes in the sources of electricity supply—from carbon-intensive, fossil-fueled power plants to zero-carbon renewable resources such as wind turbines and solar power plants—and dramatic increases in deployment of energy storage, energy-efficient technologies, and distributed energy resources (DERs). These changes create challenges for the electric power grid.

In the U.S. between 2004 and 2014, the cumulative installed capacity of renewable sources of power generation increased from 98 GW to over 179 GW, an 83% increase (DOE, 2014). As a percentage of total electricity generation in the U.S., renewables continue to claim a larger share as well, at almost 14% in 2014 (DOE, 2014). These trends continue across the globe. During the same time period, cumulative global renewable capacity grew from approximately 900 GW to over 1700 GW (an 88% increase), and as a percentage of total global electricity generation, renewables accounted for almost 24% in 2014 (DOE, 2014).

Zero-carbon renewable sources of energy for electricity supply will unquestionably play a critical role in decarbonization, but they challenge traditional power-system operations and planning in several ways. Increases in generation from variable resources such as wind and solar create a need for an increasingly flexible system able to withstand rapid fluctuations in power output. While some of this flexibility can be accomplished through better coordination of existing generation resources, investments in additional flexibility-lending, and fast-response generation capacity, such as natural gas-fired combustion turbines or battery energy storage, are also needed.

Additionally, while the growth of average electricity loads has stagnated due to increased energy conservation, energy efficiency, customer load-shifting behaviors, demand response programs and more on-site electricity generation, peak-to-average demand ratios have continued to grow (EIA, 2014). This is important because to maintain grid reliability standards, power-system planners need to continue designing a power system able to supply power even at the times of highest demand. This raises the challenge of allocating (new and existing) resources to provide reliable power during the peakiest of times.

Unfortunately, it is often flexibility-enhancing resources that face strong investment disincentives under existing competitive electricity market designs. Falling prey to a "missing money" problem, these resources do not receive high enough electricity prices during the relatively few periods of demand when they are called upon in order to fully recover costs (Hogan, 2013; Shanker, 2003). There are ongoing efforts in electricity markets around the world to better align market products and pricing with the grid services flexibility resources actually provide through better scarcity pricing and capacity markets, as well as new "intra-day" electricity markets for balancing supply with demand (Hogan, 2013; Cramton *et al.*, 2013; EPEX SPOT, 2010).

Over the last decade, the deployment of distributed energy resources (DERs) has skyrocketed. This growth has included rooftop solar PV, but demand response, micro-wind turbines, on-site energy storage, and electric vehicles are also growing. As of the first quarter of 2016, one million U.S. homes have rooftop solar PV panels (SEIA, 2016). This has been met with rapid expansion of advanced metering infrastructure (AMI) as well—as of 2014, the U.S. had close to 60 million AMIs installed, 88% of which were residential (EIA, 2016b). This proliferation of DERs, combined with increased consumer participation in energy generation and consumption, has led to a new paradigm for power grids. The century-old power system with large centralized power plants generating and transmitting electricity one-way through a network of transmission and distribution lines to end-users is in the process of being reconstituted into a two-way system with consumers active in producing power and making premeditated decisions about the amount of electricity they use and the times at which they use it. In effect, a new breed of "prosumers" at the original "meter-end" of the electric power system has been born.

A central challenge with increased DERs in electric power systems is lost distribution utility revenue. End-users with "behind-the-meter" distributed generation, such as rooftop solar panels, are now generating at least a portion of the electricity they consume onsite. DERs thus decrease the amount of electricity (kWh) they purchase from their local distribution utility, which in turn leads to decreased utility revenues (utilities charge end-users using volumetric ($/kWh) rates). Additionally, during the day, most customers with solar PV panels produce more electricity than they consume, and thus export this power to the grid. Net metering policies have provided customers with the ability to reduce their electricity bills by the number of kWhs they export to the grid during these times of excess generation.

Box 13.

Renewables and the 2°C Challenge

Large-scale penetration of renewable energy sources such as wind and solar require a combination of further improvements in the base technology (especially various solar technologies), advances in energy storage, and the ability to operate the electric grid to more effectively take advantage of these intermittent sources. Solar needs to address all three challenges. Wind is currently mostly competitive on leveled cost of electricity, but the challenges related to storage and the grid still need to be solved.

Figures 31 and 32 show global primary energy and electricity generation under a 2°C scenario in which renewables are assumed to have the cost advantage, and are not limited by storage or the grid, and therefore dominate over other technologies. Specifically, we assume that renewables are low-cost, bioenergy and CCS are at their base (median) costs, and nuclear is constrained. When nuclear is constrained and renewables costs fall, renewables can be a dominant energy and electricity source.

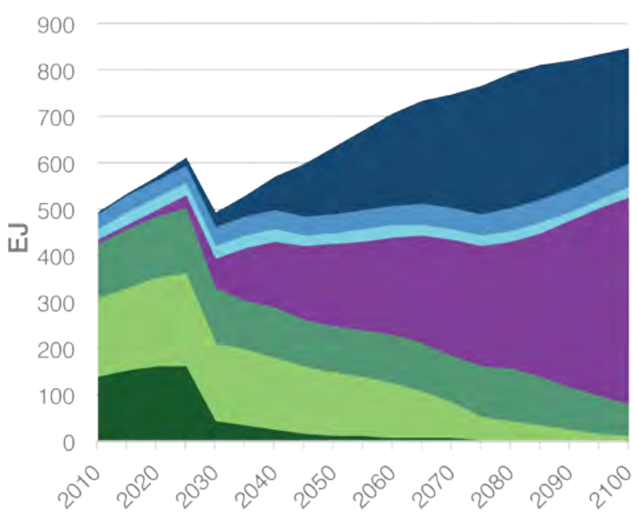


Figure 31. Global Primary Energy (exajoules) under the 2°C scenario with low renewables costs and constrained nuclear and median climate response

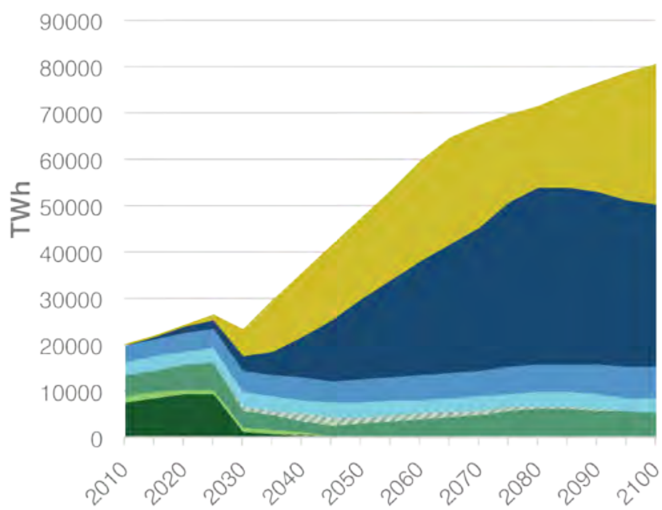


Figure 32. Global Electricity Production (TWh) under the 2°C scenario with low renewables costs and constrained nuclear and median climate response

Bioelectricity | Renewables (Wind & Solar) | Hydro | Nuclear | Bioenergy | Gas (w/CCS) | Gas (no CCS) | Oil | Coal (w/CCS) | Coal (no CCS)

Distribution utility revenues then drop further as customers are charged for fewer and fewer kWh of electricity. Unfortunately, as the number of kWh sales decreases, utilities have to increase their charges to continue recovering costs. These rate increases can be substantial, incentivizing even more DER adoption as customers seek to avoid paying higher electricity bills. As one example of such a rate increase, each investor-owned utility in California induced an approximately 100% increase in their distribution charges from 2003 to 2014 (Wolak, 2016).

A related challenge is that today's volumetric ($/kWh) rates simply do not reflect the true costs that distribution utilities incur to acquire and deliver reliable electricity to end-users. DERs impose many new costs to electricity grids, such as increased capacity investments to manage new ramping needs and stability requirements; more routine grid maintenance; and new physical infrastructure to deploy and support AMI and new interconnections to relieve congestion. Cost-causation principles can be considered to more adequately reflect these costs in the charges consumers see on their electricity bills such that distribution utilities are not disincentivized from supporting further DERs. There are many diverse proposals for what these tariffs should look like, but in general it is useful to separate the fraction of network cost that does not depend on consumer behavior, and allocate the rest based on cost responsibility. In this case, individual-use profiles will govern what is paid (Pérez-Arriaga and Bharatkumar, 2014).

Overall, the presence of DERs is forcing planners to abandon the customary "electricity trickling down" mindset and replace it with one in which DERs have an equal footing with centralized resources in providing grid services (Pérez-Arriaga, 2016). This overhaul is requiring review and redesign of the traditional distribution regulatory paradigm, utility business models, and even the physical structure of the system. With respect to grid services, DERs are able to provide several services besides real energy, such as peak-demand reduction, reactive power for voltage support, and a host of additional ancillary services. These services afford opportunities for creating not only new electricity markets and products, but also entirely new business models for distribution utilities and new distribution-level actors (Fitzgerald *et al.*, 2015; Florence School of Regulation, 2012; Jenkins and Pérez-Arriaga, 2017). Opportunities to aggregate numerous residential DER owners, to provide and be compensated for specific grid services or facilitate local markets managing the two-way purchases and sales of energy resources on distribution, and bulk-system grids are just two of many new roles on the transitioning grid.

Distribution regulatory policy redesign needed to realize such changes has been initiated in power systems across the world. In the U.S., the State of New York is continuing to proceed with its 2014-launched "Reforming the Energy Vision" (NYREV). NYREV is the first attempt in the U.S. to comprehensively reform regulatory policy for distribution utilities, aimed specifically at adapting the power system to increased levels of DERs. The proceeding's overall mission is to better align utility business models and revenues with the services that DERs can provide to the power system, through improved regulation, market offerings and pricing structures (NY DPS, 2014). California has also made noteworthy progress in improving distribution regulatory policy, ratemaking practices and new utility business models. In April 2016, the California Public Utilities Commission (CPUC) proposed a new ruling that would allow distribution utilities to earn a rate of return on procurement of DERs via contracts. While allowing owners of distribution grids financial rights in DERs can create its own challenges, this has been a step forward in relieving the disincentive utilities face in supporting DERs that can decrease their kWh sales (CPUC, 2016). Meanwhile, in the U.K., the RIIO (Revenue = Incentives + Innovation + Outputs) framework is already in its implementation phases. Announced in March 2013, RIIO is the U.K.'s strategy for regulatory reform at the transmission and distribution-network levels, for both gas- and electricity-delivering utilities. The framework is a variant of traditional performance-based regulation, tying the utility's remuneration to its actual output, but also expanding the definition of "performance" to include expected reliability and customer satisfaction targets, and opportunities to undertake innovation projects. RIIO's main objective is to incentivize utilities to continue investing in modernizing the network for increased DERs and other low-carbon solutions. As of 2016, RIIO is currently in its final phase of its determinations and launch (Ofgem, 2016).

Nidhi is a Postdoctoral Associate at the MIT Energy Initiative. Francis O'Sullivan is director of research for the MIT Energy Initiative, and a senior lecturer at the MIT Sloan School of Management.

Carbon Capture and Storage

By Howard Herzog

Carbon capture and sequestration (CCS) is technically viable today as a strategy to reduce anthropogenic carbon dioxide (CO_2) emissions linked to rising global temperatures. It facilitates power that can be dispatched around the clock, as opposed to intermittent power from wind and solar; it's the primary option for energy-intensive industries such as cement, refineries, petrochemicals, and iron and steel; it's the only mitigation technology that can rescue potentially hundreds of trillions of dollars of stranded fossil assets; and it provides the major pathway to negative emissions when combined with biomass-fired power plants.

Despite these inherent strengths, CCS has been implemented at very few sites where fossil fuel combustion occurs—one power plant, two more under construction, and about 20 industrial facilities to date—due to high energy and capital costs. These costs are likely to remain the biggest challenge to its widespread adoption, since it's always cheaper to emit CO_2 into the atmosphere than to capture and store it. Making CCS economically viable in the near future will require policies that put the globe on a climate stabilization pathway and encourage research in low-carbon energy solutions.

Investment in CCS research could advance a wide range of approaches aimed at dramatically lowering the cost of carbon capture. These include new solvents that improve the efficiency of the standard process, which entails chemical scrubbing to remove CO_2 from power plant or industrial process exhaust gases (termed post-combustion); new materials such as adsorbents and membranes that could eliminate the need for chemical scrubbing; and new processes designed to make capture easier.

Alternative processes include oxy-combustion and pre-combustion. In oxy-combustion, fossil fuels are combusted using high-purity oxygen rather than air, thereby increasing the concentration of CO_2 so it can be more easily captured. In pre-combustion, coal is converted to gas through a series of chemical reactions that result in separate streams

Saskatchewan, Canada: SaskPower Boundary Dam, the world's first carbon capture and sequestration (CCS) power plant.

of CO_2 for capture and hydrogen for electricity generation.

Because post-combustion capture is already established as a commercial technology today, oxy-combustion must show clear advantages in order to have significant market penetration. Currently, there is very little field experience with oxy-combustion power plants, but oxy-combustion has been attempted in other industries. A major effort is underway to dramatically reduce the cost of oxygen; one example is investigating the possibility of integrating ionic transport membranes into power boilers. Meanwhile, research is continuing on what are usually characterized as advanced oxy-combustion technologies: chemical looping and solid oxide fuel cells (SOFC).

The biggest challenge for pre-combustion capture is to make an integrated coal gasification combined cycle (IGCC) power plant competitive in cost to a pulverized coal (PC) power plant. A few years back, it was thought that capital costs for IGCC plants could be lowered to within 10% of those of a PC plant. While hard numbers are difficult to obtain, it seems the gap is greater than 30% today. Another challenge for IGCC plants is to accept a wider variety of feedstocks, specifically low-ranked coals with high ash or water content.

Capturing CO_2 from IGCC plants is relatively straight-forward. The capital and energy requirements for pre-combustion capture are significantly less than post-combustion capture. However, those advantages cannot overcome the current premium required to build an IGCC plant (versus a PC plant).

Through the Paris agreement, nearly 200 nations established greenhouse gas emissions reduction pledges through the year 2030, but these commitments amount to less than 20 percent of the cuts needed for climate stabilization, and can be achieved without the use of CCS. There is, however, a very good chance that significant CCS deployment will be needed to enable countries to fulfill more ambitious pledges that will be expected of them in the decades to come. By making investments to facilitate the dramatic reduction of CO_2 emissions that will be required, government and industry could and should do a lot more to move the technology forward.

Howard Herzog is a senior research engineer and CCS expert at the MIT Energy Initiative.

Box 14.

CCS and the 2°C Challenge

Figures 33 and 34 show global primary energy and electricity generation under a 2°C scenario in which CCS is assumed to have the cost advantage and therefore dominate over other technologies. Here we assume that CCS is low cost, bioenergy and renewables are at their base costs, and nuclear is constrained. When nuclear is constrained and the CCS technology costs are reduced, a modest amount of natural gas with CCS (about 13% of generation by 2100) enters the electricity mix. However, bioenergy dominates in this case. Biomass with CCS was not included as an option in these scenarios. A challenge for CCS with coal, oil or gas is that as currently envisioned, the capture rate is expected to be about 90%. For very low emissions scenarios, and high CO_2 prices needed to achieve them, the 10% emissions rate combined with lower overall conversion efficiency is not insignificant, especially for coal power. If the technological advances overcome these issues or costs of other technologies are above median estimates, CCS could play a larger role. If CCS is combined with biomass to create a negative emissions technology, and storage capacity is not limited, other studies suggest an even larger role.

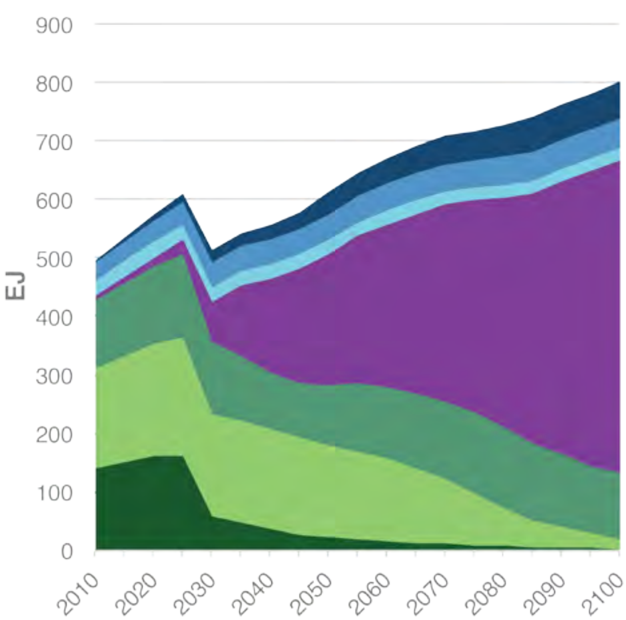


Figure 33. Global Primary Energy (exajoules) under the 2°C scenario with low CCS costs and constrained nuclear and median climate response

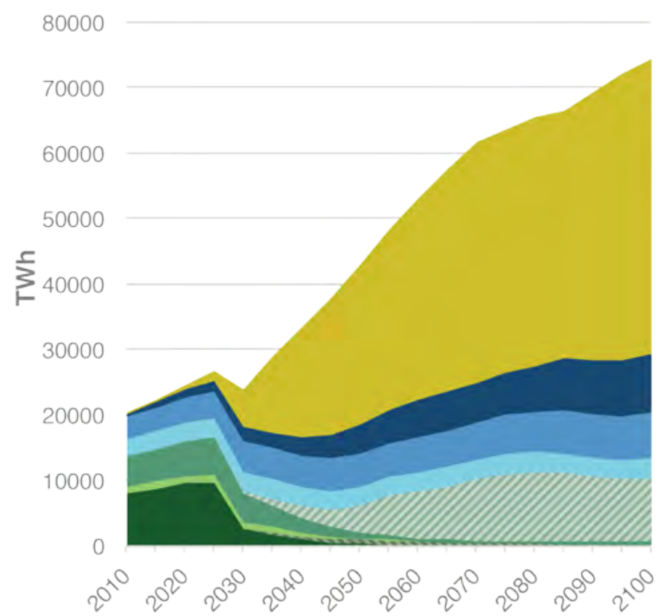
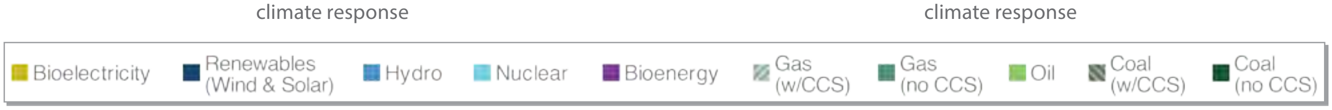


Figure 34. Global Electricity Production (TWh) under the 2°C scenario with low CCS costs and constrained nuclear and median climate response



Preparing for Tomorrow Today

Absent further mitigation, the world faces the challenge of adapting to a rapidly changing climate—not only its effects on water and crops as described in this Outlook, but also threatened coastal infrastructure due to rising sea levels and increased storms, risks to human health, lowered labor productivity and degraded natural ecosystems. When it comes to feeding the world and providing adequate fresh water supplies, these systems already face challenges from population growth to coastal development, and such increasing pressures may often be exacerbated by climate change.

A major challenge in investigating these impacts and potentially adapting to them is that our ability to predict outcomes remains weak. So far there has not been a significant sustained research effort over decades to develop models and tools to project climate impacts on systems of importance to human activity and the sustainability of ecosystems and the Earth system. Over the past five to 10 years, however, the problem has received much more attention, resulting in significant advances. Considering the relatively early stage of this modeling and research, there is reason to expect that with more dedicated effort, the marginal improvement in these models and projections will be high.

Given the risks we face with climate change, continued effort to reduce emissions is critical, and further investment in R&D that would lower the cost of low-GHG alternatives would make the task of reducing emissions toward zero easier, and likely facilitate implementation of international climate agreements.

To meet a goal of stabilizing GHG concentrations (at any level) will ultimately require near-zero, and ultimately zero, net emissions. This will require drastic changes in the global energy mix, and to achieve the goal of staying below 2°C or even aiming for 1.5°C, this transformation will need to be well underway within the next 10 to 20 years. While there currently exist technologies to enable this transformation, the cost of mitigation could be greatly reduced by advances in key energy technologies. In this Outlook we have demonstrated some challenges and ways forward for nuclear, bioenergy, solar, energy storage, the electric grid and carbon capture and storage. We will also need to consider mitigation of methane and nitrous oxide from agriculture, CO_2 from land-use change, as well as continued efforts to improve energy efficiency, which could significantly reduce the need for expanded energy production. With the right economic incentives, the need for new energy sources and greater energy efficiency can provide market opportunities for companies with innovative solutions.

References

Outlook References:

Blanc, É., 2016: Statistical Emulators of Maize, Rice, Soybean and Wheat Yields from Global Gridded Crop Models. MIT Joint Program on the Science and Policy of Global Change *Report 296* (http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt296.pdf).

Blanc, É., K. Strzepek, C.A. Schlosser, H. Jacoby, A. Gueneau, C. Fant, S. Rausch & J. Reilly, 2014: Modeling U.S. water resources under climate change. *Earth's Future*, 2(4): 197–224 (doi: 10.1002/2013EF000214). [See Reprint 2014-17]

Blanc, É. & B. Sultan, 2015: Emulating maize yields from global gridded crop models using statistical estimates. *Agricultural and Forest Meteorology*, 214-215: 134–147 (doi:10.1016/j.agrformet.2015.08.256). [See Reprint 2015-29]

Bolinger, M. & J. Seel, 2015: *Utility-Scale Solar 2014: An Empirical Analysis of Project Cost, Performance, and Pricing Trends in the United States* (https://emp.lbl.gov/publications/utility-scale-solar-2014-empirical).

BP, 2016: *Statistical Review of World Energy*. BP plc, London, U.K.

Chung, D., C. Davidson, R. Fu, K. Ardani & R. Margolis, 2015: *U.S. Photovoltaic Prices and Cost Breakdowns: Q1 2015 Benchmarks for Residential , Commercial , and Utility-Scale Systems*. National Renewable Energy Laboratory (http://www.nrel.gov/docs/fy15osti/64746.pdf).

Chung, D., E. Elgqvist & S. Santhanagopalan, 2016: Automotive Lithium-ion Cell Manufacturing: Regional Cost Structures and Supply Chain Considerations. April 2016. National Renewable Energy Laboratory (http://www.nrel.gov/docs/fy16osti/66086.pdf).

CPUC [California Public Utilities Commission], 2016: *Distributed resources plan draft proposal*. (http://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M159/K702/159702148.pdf).

Cramton, P., A. Ockenfels & S. Stoft, 2013: Capacity Market Fundamentals. *Economics of Energy and Environmental Policy*, 2(2): 27–46.

DOE [U.S. Department of Energy], 2010: *Grid-Scale Rampable Intermittent Dispatchable Storage ARPA-E Funding Opportunity Announcement*. Washington DC (https://arpa-e-foa.energy.gov/FileContent.aspx?FileID=98c6222e-471c-4216-a377-024dbdb45549).

DOE [U.S. Department of Energy], 2014: *2014 Renewable Energy Data Book*. Office of Energy Efficiency and Renewable Energy. (http://www.nrel.gov/docs/fy16osti/64720.pdf).

DOE [U.S. Department of Energy], 2016: Global Energy Storage Database. U.S. Department of Energy (http://www.energystorageexchange.org).

EIA [U.S. Energy Information Administration], 2014: Peak-to-average electricity demand ratio rising in New England and many other U.S. regions. (http://www.eia.gov/todayinenergy/detail.cfm?id=15051).

EIA [U.S. Energy Information Administration], 2016a: *Annual Energy Outlook*. U.S. Energy Information Administration, Washington, DC.

EIA [U.S. Energy Information Administration], 2016b: Website: "How many smart meters are installed in the United States, and who has them?" (http://www.eia.gov/tools/faqs/faq.cfm?id=108&t=3).

EPEX SPOT [European Power Exchange], 2010: Continuous cross-border intraday trading mechanism on France-Germany using ComXerv. (http://static.epexspot.com/document/10248/20100910_FR-DE_IDCB_Forum_Dusseldorf_EPEX.pdf).

EPRI [Electric Power Research Institute], 1994: "History of First U.S. Compressed-Air Energy Storage (CAES) Plant (110MW 26h): Vol 2: Construction." http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=TR-101751-V2, accessed 10/10/14.

Energy Storage Association, 2016: *US Energy Storage Market Grew 243% in 2015, Largest Year on Record*. 3/3/16. (http://energystorage.org/news/esa-news/ us-energy-storage-market-grew-243-2015-largest-year-record).

Fant, C., C.A. Schlosser, X. Gao, K. Strzepek & J. Reilly, 2016: A Framework for Analysis of the Uncertainty of Socioeconomic Growth and Climate Change on the Risk of Water Stress: a Case Study in Asia. *PLoS ONE* 11(3): e0150633 (doi: 10.1371/journal.pone.0150633). [See Reprint 2016-6]

Fitzgerald, G., J. Mandel, J. Morris & H. Touati, 2015: The Economics of Battery Energy Storage: How multi-use, customer-sited batteries deliver the most services and value to customers and the grid. Rocky Mountain Institute, September 2015 (http://www.rmi.org/electricity_battery_value).

Florence School of Regulation, 2012: From Distribution Networks to Smart Distribution Systems: Rethinking the Regulation of European Electricity DSOs. *THINK Project Report No. 12* (http://www.eui.eu/Projects/THINK/Research/Topic12.aspx).

Forest, C.E., P.H. Stone & A.P. Sokolov, 2008: Constraining climate model parameters from observed 20th century changes. *Tellus A*, 60(5): 911–920 (doi: 10.1111/j.1600-0870.2008.00346.x).

Hogan, W., 2013: Electricity Scarcity Pricing through Operating Reserves. *Economics of Energy & Environmental Policy*, 2(2): 65–86. (Draft: http://www.ksg.harvard.edu/fs/whogan/Hogan_ORDC_042513.pdf).

Huang, J., R. Wang, R. Prinn & D. Cunnold, 2009: A semi-empirical representation of the temporal variation of total greenhouse gas levels expressed as equivalent levels of carbon dioxide. MIT Joint Program on the Science and Policy of Global Change *Report 174* (http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt174.pdf).

IEA/NEA [International Energy Agency/Nuclear Energy Agency], 2015: *Projected Costs of Generating Electricity, 2015 Edition*. Organisation for Economic Co-operation and Development, France.

IMF [International Monetary Fund], 2015: World Economic and Financial Surveys: World Economic Outlook Database, Washington DC, USA (http://www.imf.org/external/pubs/ft/weo/2015/01/weodata/download.aspx).

IMF [International Monetary Fund], 2016: World Economic and Financial Surveys: World Economic Outlook Database, Washington DC, USA (http://www.imf.org/external/pubs/ft/weo/2016/01/weodata/download.aspx).

IPCC, 2013: Summary for Policymakers, in: *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex & P.M. Midgley (eds.), Cambridge University Press, Cambridge, United Kingdom & New York, NY, USA.

ITRPV [International Technology Roadmap for Photovoltaic], 2016: *2015 Results*. (http://www.itrpv.net/Reports/Downloads/2016).

Jenkins, J.D. & I.J. Pérez-Arriaga., 2017: Improved regulatory approaches for the remuneration of electricity distribution utilities with high penetrations of distributed energy resources. *Energy Journal*, 38(1), in press.

Kojima, A., K. Teshima, Y. Shirai & T. Miyasaka, 2009: Organometal halide perovskites as visible-light sensitizers for photovoltaic cells. *Journal of the American Chemical Society* 131, 6050–6051.

Mints, P., 2015: Photovoltaic technology trends: a supply perspective. *SPV Market Research in collaboration with IDTechEx* (http://www.idtechex.com/research/articles/global-photovoltaic-shipments-jump-15-in-2014-00007454.asp?donotredirect=true).

Nakićenović, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K. Gregory, A. Griibler, T.Y. Jung, T. Kram, E. Lebre La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor & Z. Dadi, 2000: *IPCC special report on emissions scenarios*. Cambridge University Press, Cambridge, UK & New York, NY, USA.

NBS [National Bureau of Statistics], 2013: *China Energy Statistical Yearbook*. Beijing, China.

NBS [National Bureau of Statistics], 2014: *China Energy Statistical Yearbook*. Beijing, China.

NREL [National Renewable Energy Laboratory], 2015: Best Research-Cell Efficiencies. (http://www.nrel.gov/ncpv/images/efficiency_chart.jpg).

NY DPS [New York Department of Public Service], 2014: *Reforming the Energy Vision Staff Report and Proposal*. April 2014 (http://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId=%7B5A9BDBBD-1EB7-43BE-B751-0C1DAB53F2AA%7D).

Nykvist, B. & M. Nilsson, 2015: Rapidly falling costs of battery packs for electric vehicles. *Nature Climate Change*, 5(April): 329–332.

Ofgem, 2016: *Price controls explained.* RIIO Factsheet (https://www.ofgem.gov.uk/ofgem-publications/64003/pricecontrolexplainedmarch13web.pdf).

Paltsev, S., J. Reilly & A. Sokolov, 2013: What GHG Concentration Targets are Reachable in this Century? MIT Joint Program on the Science and Policy of Global Change *Report 247*, (http://globalchange.mit.edu/research/publications/2460).

Pérez-Arriaga, I.J., 2015: *Storage, renewables, and the evolution of the grid: regulation, policy, and market design*. Prepared for: MITEI Associate Member Symposium on Energy Storage, May 2015.

Pérez-Arriaga, I.J. & A. Bharatkumar, 2014: A Framework for Redesigning Distribution Network Use of System Charges Under High Penetration of Distributed Energy Resources: New Principles for New Problems. MIT Center for Energy and Environmental Policy Research Working Paper *CEEPR WP 2014–006* (http://ceepr.mit.edu/publications/working-papers/614).

Pérez-Arriaga, I.J., 2016: "Implementing Better Markets: Moving Theory to Practice." Presentation at the MITEI Associate Member Symposium, May 3, 2016, Cambridge, MA.

REN21, 2016: *Renewables 2016 Global Status Report.* (http://www.ren21.net/status-of-renewables/global-status-report/).

Sakti, A., R. Miller & F. Brushett, 2015: What's cost got to do with it?—An assessment of Tesla's Powerwall. *MITEI News*, June 2015 (http://energy.mit.edu/news/whats-cost-got-to-do-with-it/).

Sakti, A. & F. O'Sullivan, 2016: Synthesis report on 2015 MITEI Associate Member Symposium—Storage Renewables and Evolution of the Grid. (http://energy.mit.edu/wp-content/uploads/2016/06/2015-Associate-Member-Symposium-Report.pdf).

Schlosser, C.A., X. Gao, K. Strzepek, A. Sokolov, C.E. Forest, S. Awadalla & W. Farmer, 2012: Quantifying the Likelihood of Regional Climate Change: A Hybridized Approach. *Journal of Climate* 26(10): 3394–3414 (doi: 10.1175/JCLI-D-11-00730.1).

Schlosser, C.A., K. Strzepek, A. Gueneau, C. Fant, X. Gao, É. Blanc, H. Jacoby, & J. Reilly, 2014: The future of global water stress: An integrated assessment. *Earth's Future* (doi:10.1002/2014EF000238). [See Reprint 2014-16]

SEIA, 2016: *Q2 2016 U.S. Solar Market Insight.* (http://www.greentechmedia.com/research/subscription/u.s.-solar-market-insight).

Shanker, R., 2003: Comments on Standard Market Design: Resource Adequacy Requirement. Federal Energy Regulatory Commission Docket RM01-12-000. Retrieved from: http://elibrary.ferc.gov/idmws/common/opennat.asp?fileID=9619272.

Strzepek, K., C.A. Schlosser, A. Gueneau, X. Gao, É. Blanc, C. Fant, B. Rasheed & H. Jacoby, 2013: Modeling water resource systems within the framework of the MIT Integrated Global System Model: IGSM-WRS. *Journal of Advances in Modeling Earth Systems,* 5(3): 638–653 (doi: 10.1002/jame.20044). [See Reprint 2013-26]

SunPower, 2014: *SunPower X-Series Solar Panels: Solar Panel Datasheet.* (https://us.sunpower.com/solar-resources).

USDA [U.S. Department of Agriculture], 2016: World Agricultural Production, Circular Series, WAP 6-16 (June), United States Department of Agriculture, Washington DC.

UN [United Nations], 2013: *World Population Prospects: The 2012 Revision*. Population Division, United Nations Department of Economic and Social Affairs (http://esa.un.org/unpd/wpp/Excel-Data/population.htm).

van Vuuren, D., J. Edmonds, M. Kainuma, K. Riahi & J. Weyant, 2011: A Special Issue on the RCPs. *Climatic Change*, 109(1–2): 1–4.

Winchester, N., & J.M. Reilly, 2015: The feasibility, costs, and environmental implications of large-scale biomass energy. *Energy Economics*, 51: 188–203 (doi: 10.1016/j.eneco.2015.06.016). [See Reprint 2015-17]

Wolak, F., 2016: "Integrating Distributed Energy Resources: Opportunities & Challenges." Presentation at the MITEI Associate Member Symposium, May 3, 2016, Cambridge, MA.

World Bank [Water Resources Management, Africa Region], 2010. The Zambezi River Basin: A Multi-Sector Investment Opportunities Analysis, Volume 1: Summary Report. Washington DC.

Publications describing IGSM basic structure:

Chen, Y.-H.H., S. Paltsev, J.M. Reilly, J.F. Morris and M.H. Babiker, 2016: Long-term economic modeling for climate change assessment. *Economic Modeling*, 52(B): 867–883, doi:10.1016/j.econmod.2015.10.023. [See Reprint 2016-1]

Monier, E., J.R. Scott, A.P. Sokolov, C.E. Forest and C.A. Schlosser, 2013: An integrated assessment modeling framework for uncertainty studies in global and regional climate change: the MIT IGSM-CAM (version 1.0). *Geoscientific Model Development*, 6: 2063–2085 (doi: 10.5194/gmd-6-2063-2013). [See Reprint 2013-28]

Paltsev, S., J.M. Reilly, H.D. Jacoby, R.S. Eckaus, J. McFarland, M. Sarofim, M. Asadoorian, and M. Babiker, 2005: The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. MIT Joint Program on the Science and Policy of Global Change *Report 125* (http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt125.pdf).

Prinn, R.G., 2012: Development and application of earth system models. *Proceedings of the National Academy of Sciences*, 110(S1): 3673–3680 (doi:10.1073/pnas.1107470109). [See Reprint 2012-12]

Schlosser, C.A., X. Gao, K. Strzepek, A. Sokolov, C.E. Forest, S. Awadalla and W. Farmer, 2012: Quantifying the Likelihood of Regional Climate Change: A Hybridized Approach. *Journal of Climate* 26(10): 3394–3414 (doi: 10.1175/JCLI-D-11-00730.1).

Sokolov, A.P., C.A. Schlosser, S. Dutkiewicz, S. Paltsev, D.W. Kicklighter, H.D. Jacoby, R.G. Prinn, C.E. Forest, J. Reilly, C. Wang, B. Felzer, M.C. Sarofim, J. Scott, P.H. Stone, J.M. Melillo and J. Cohen, 2005: The MIT Integrated Global System Model (IGSM) Version 2: Model Description and Baseline Evaluation. MIT Joint Program on the Science and Policy of Global Change *Report 124* (http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt124.pdf).

Applications of the IGSM are described in the Joint Program reports & peer-reviewed research available on our website: http://globalchange.mit.edu/research/publications

Appendix

This appendix contains projections for global economic growth, energy use, emissions and other variables to 2050. The projections are unchanged from the 2015 Outlook. See Box 4 (on page 8) for details. Similar tables for 16 regions of the world are available at http://globalchange.mit.edu/Outlook2016

MIT Joint Program Food, Water, Energy & Climate Outlook 2015–2016 — Projection Data Tables

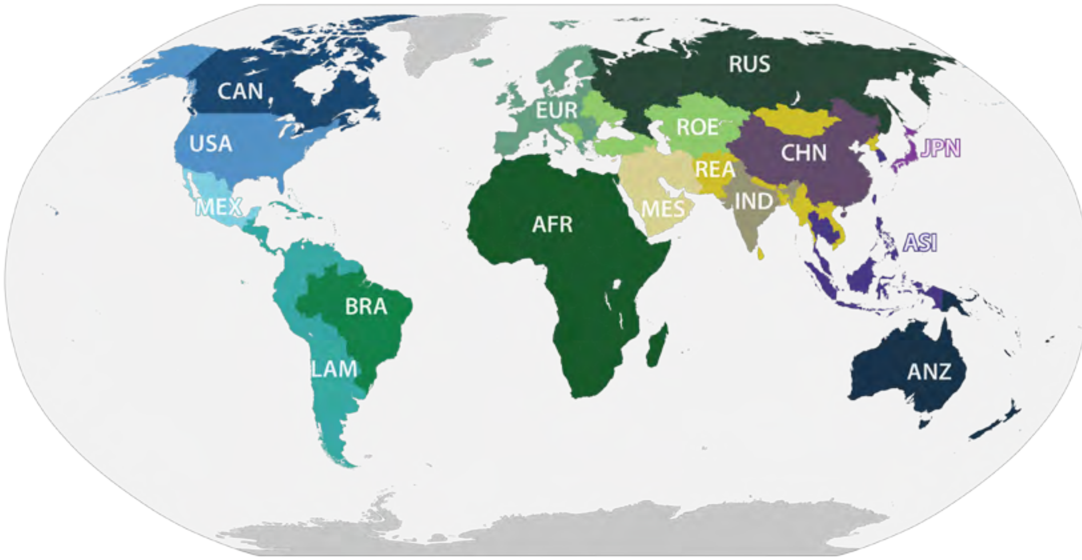
Region: World

	Units	2010	2015	2020	2025	2030	2035	2040	2045	2050
Economic Indicators										
GDP	(bil 2010 $)	52,840	59,080	67,955	78,051	89,861	102,035	115,431	130,662	148,148
Consumption	(bil 2010 $)	32,363	36,192	41,882	47,931	55,057	62,288	70,323	79,549	90,143
GDP growth	(% / yr)	1.9%	2.3%	2.8%	2.8%	2.9%	2.6%	2.5%	2.5%	2.5%
Population	(millions)	6,916.2	7,324.8	7,716.8	8,083.4	8,424.9	8,743.4	9,038.7	9,308.4	9,550.9
GDP *per capita*	(2010 $)	7,640	8,066	8,806	9,656	10,666	11,670	12,771	14,037	15,511
GHG Emissions										
CO_2 – fossil	(Mt CO_2)	30,944	33,071	33,416	35,354	36,868	38,311	39,417	40,614	42,090
CO_2 – industrial	(Mt CO_2)	1,564	1,894	2,050	2,032	1,739	1,542	1,628	1,687	1,720
CH_4	(Mt)	335.00	359.80	369.30	396.00	405.90	427.00	446.00	466.10	492.10
N_2O	(Mt)	11.62	11.67	12.02	12.53	12.75	13.61	14.46	15.36	16.40
PFCs	(kt CF_4)	14.62	7.93	5.57	5.64	5.38	5.76	5.97	6.06	6.35
SF_6	(kt)	6.38	5.11	5.21	5.72	6.43	6.59	7.29	7.83	8.36
HFCs	(kt HFC-134a)	349	224	187	167	166	188	219	248	281
Total GHG net of Land Use	(Mt CO_2e)	45,668	48,598	49,394	52,184	53,752	55,856	57,861	59,969	62,541
CO_2 – land use change	*(Mt CO_2)*	*2,560*	*2,580*	*1,972*	*1,841*	*2,125*	*1,317*	*1,369*	*1,286*	*1,218*
Primary Energy Use	**(EJ)**									
Coal		140.5	153.6	148.5	152.9	156.5	156.7	155.2	157.8	159.5
Oil		175.9	182.6	189.3	200.0	208.4	218.2	227.9	237.0	249.2
Biofuels		2.3	2.9	3.9	4.5	5.9	6.8	7.1	8.0	8.3
Gas		109.0	118.0	124.4	139.7	152.2	165.5	176.3	182.7	191.4
Nuclear		27.6	27.3	30.7	34.6	40.0	41.3	48.7	58.8	73.2
Hydro		31.3	32.9	37.6	39.6	43.3	48.8	52.5	57.7	63.6
Renewables		7.5	8.7	14.1	20.3	27.2	34.3	41.4	48.8	56.7
Electricity Production	**(TWh)**									
Coal		8,090	9,289	9,522	9,788	10,001	10,129	10,038	10,168	10,034
Oil		1,391	1,577	1,690	1,780	1,829	1,853	1,886	1,936	1,974
Gas		4,120	4,528	5,089	6,086	6,799	7,634	8,380	8,717	9,058
Nuclear		3,018	2,873	3,151	3,452	3,859	4,002	4,573	5,354	6,450
Hydro		3,104	3,235	3,594	3,765	4,111	4,545	4,844	5,283	5,778
Renewables		815	926	1,462	2,096	2,807	3,512	4,226	4,975	5,784
Household Transportation										
Number of vehicles	(millions)	808	884	978	1,069	1,163	1,239	1,316	1,410	1,514
Vehicle miles traveled	(trillions)	6.67	7.48	8.50	9.50	10.59	11.50	12.41	13.48	14.70
Miles per gallon	(mpg)	22.80	24.50	25.20	26.40	27.20	27.70	28.00	28.10	28.10
Vehicles per person		*0.12*	*0.12*	*0.13*	*0.13*	*0.14*	*0.14*	*0.15*	*0.15*	*0.16*
Land Use	**(Mha)**									
Cropland		1,552.2	1,543.8	1,538.6	1,559.7	1,576.1	1,613.1	1,628.5	1,651.9	1,676.4
Biofuels		38.6	45.8	53.3	53.8	54.8	48.8	45.3	44.0	41.2
Pasture		3,035.4	3,146.7	3,247.7	3,269.9	3,270.8	3,279.3	3,294.4	3,306.0	3,326.6
Managed forest		727.7	724.8	720.8	721.4	713.8	706.3	703.4	698.6	691.6
Natural grassland		1,870.5	1,779.6	1,692.6	1,662.4	1,659.4	1,642.3	1,633.5	1,621.3	1,601.2
Natural forest		3,380.7	3,363.2	3,339.6	3,313.4	3,290.0	3,264.7	3,240.5	3,215.5	3,193.0
Other		2,659.6	2,659.6	2,659.6	2,659.6	2,659.6	2,659.6	2,659.6	2,659.6	2,659.6
Air Pollutant Emissions	**(Tg)**									
SO_2		103.03	103.85	101.25	100.97	99.28	95.92	91.82	88.93	86.15
NO_x		119.82	132.18	143.64	158.89	174.19	187.37	199.20	213.07	228.24
Ammonia		48.30	54.46	61.59	67.02	70.38	75.89	80.86	86.00	91.15
Volatile organic compounds		110.17	119.40	132.20	147.79	162.86	175.98	187.47	198.65	212.11
Black carbon		5.52	5.45	5.59	5.77	5.87	5.90	5.69	5.51	5.35
Organic particulates		12.56	12.60	13.55	14.15	14.65	14.96	14.43	14.02	13.65
Carbon monoxide		549.39	613.33	700.31	806.51	913.59	1,016.57	1,114.38	1,215.07	1,324.01

IGSM regions:

AFR	Africa
ANZ	Australia & New Zealand
ASI	Dynamic Asia
BRA	Brazil
CAN	Canada
CHN	China
EUR	Europe (EU+)
IND	India
JPN	Japan
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/Outlook2016



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

Country	Region
Congo, Dem. Rep. (Zaire)	AFR
Cook Islands	ANZ
Costa Rica	LAM
Croatia	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

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

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

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

2016 Joint Program Reports *(as of October 2016)*

These and previous reports are available open-access on our website: http://globalchange.mit.edu/research/publications/reports

Report 291: Scenarios of Global Change: Integrated Assessment of Climate Impacts
Report 292: Costs of Climate Mitigation Policies
Report 293: Uncertainty in Future Agro-Climate Projections in the United States and Benefits of Greenhouse Gas Mitigation
Report 294: The Future of Natural Gas in China: Effects of Pricing Reform and Climate Policy
Report 295: Are Land-use Emissions Scalable with Increasing Corn Ethanol Mandates in the United States?
Report 296: Statistical Emulators of Maize, Rice, Soybean and Wheat Yields from Global Gridded Crop Models
Report 297: Electricity Investments under Technology Cost Uncertainty and Stochastic Technological Learning
Report 298: Modeling Regional Carbon Dioxide Flux over California using the WRF-ACASA Coupled Model
Report 299: The Impact of Coordinated Policies on Air Pollution Emissions from Road Transportation in China
Report 300: The Impact of Water Scarcity on Food, Bioenergy and Deforestation
Report 301: Combining Price and Quantity Controls under Partitioned Environmental Regulation
Report 302: 21st Century Changes in U.S. Heavy Precipitation Frequency Based on Resolved Atmospheric Patterns
Report 303: Scaling Compliance with Coverage? Firm-level Performance in China's Industrial Energy Conservation Program

MIT Joint Program Sponsors

The work of the MIT Joint Program on the Science and Policy of Global Change is funded by an international partnership of government, industry and foundation sponsors, and by private donations. The consortium provides the long-term substantial commitment needed to support our dedicated and specialized staff, and to realize a coordinated integrated research effort.

Current sponsors are also listed at: http://globalchange.mit.edu/sponsors/all

Corporate Sponsors

BP
Cargill
Centro Mario Molina
Chevron
ClearPath Foundation
CLP Holdings
ConocoPhillips
Dow Chemical
Duke Energy
Electric Power Research Institute
Electricité de France
Eni
Exelon
ExxonMobil
General Motors
Hancock Natural Resource Group
Institute of Nuclear Energy Research
J-Power
Lockheed Martin
Murphy Oil
Nike
Norwegian Ministry of Petroleum & Energy
Oglethorpe Power Corporation
Shell International Petroleum
Statoil
Tokyo Electric Power Company
Total
Toyota Motor North America
Vetlesen Foundation
Weyerhauser Company

U.S. Government Funding

U.S. Department of Agriculture [USDA]
Department of Energy [DOE]
Department of Transportation [DOT]
Energy Information Agency [EIA]
Environmental Protection Agency [EPA]
Federal Aviation Administration [FAA]
National Aeronautics & Space Administration [NASA]
National Oceanic & Atmospheric Administration [NOAA]
National Renewable Energy Laboratory [NREL]
National Science Foundation [NSF]

Photo Credits & Copyrights

MIT Joint Program: Science and Policy Working Together.

*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 an independent, integrative assessment of the impacts of global change and how best to respond.*

*Our team is composed of specialists working together from a wide range of disciplines, and our work combines the efforts and expertise of two complementary MIT research centers—the **Center for Global Change Science (CGCS)** and the **Center for Energy and Environmental Policy Research (CEEPR)**. We also collaborate with other MIT departments, research institutions, and nonprofit organizations worldwide.*

Co-Directors:

Professor Ronald G. Prinn
TEPCO Professor of Atmospheric Science
Director, Center for Global Change Science

Dr. John M. Reilly
Senior Lecturer, Sloan School of Management

Massachusetts Institute of Technology
77 Massachusetts Ave., E19-411
Cambridge, MA 02139 USA

T (617) 253-7492 **F** (617) 253-9845
globalchange@mit.edu
http://globalchange.mit.edu/