Summer 2015

ENERGY, THE ENVIRONMENT, AND CLIMATE CHANGE

The BRIDGE

LINKING ENGINEERING AND SOCIETY

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John M. Reilly

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The
BRIDGE

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From the Editor in Chief

Ronald M. Latanision (NAE) is a senior fellow at Exponent, Inc. in Natick, MA.

First, I want to thank guest editor **Bob Armstrong** for assembling a superb issue on the challenges in moving forward to meet both the growing demand for energy and the growing concern of global warming and its impacts on the lives of those who do and who will inhabit the Earth.

In this issue we continue with our interviews of engineers who have affected the culture of this nation in many ways beyond what one typically envisions of engineers. Recent issues presented interviews with poet Richard Blanco, former New Hampshire governor and chief of staff of the Bush (41) White House **John Sununu**, and writer **Henry Petroski**. This issue features former NFL player Charley Johnson.

Charley has had a remarkable career: he is a PhD chemical engineer who was an NFL quarterback, a professor of chemical engineering, and the founder of a compressor company that served the oil and gas industry. As always, managing editor Cameron Fletcher joined me in the conversation.

I did ask Charley about Deflategate. As it happens, we spoke on the day that the NFL draft began and before the Wells Report was issued. His response was predictable for a chemical engineer and even for this materials engineer (who happens to be a fan of Tom Brady and the Patriots!). Of course, I have always had a passion for sports and so I am concerned about the integrity of sports in general. But it seems an interesting and perhaps troubling statement of our times that so much attention has been directed to this issue. At any rate, Cameron and I enjoyed this conversation with Charley.

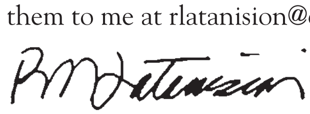
We also introduce in this issue a new dimension for the *Bridge*, op-eds. We now believe, based on the number of comments that we receive from our readers, that an op-ed column is a useful addition. It gives us the flexibility to accommodate viewpoints other than those expressed by our authors and to introduce in a timely manner a perspective or opinion on matters of importance to our readers that go beyond what appears in a given thematic issue.

We are mindful that this must be managed carefully, and so have crafted the following guidelines:

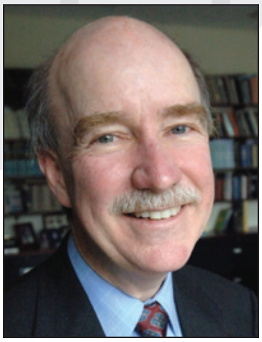
- We have adopted the standard of major daily newspapers, namely, that submissions of any length are welcomed, but those longer than 800 words are unlikely to be accepted.
- The editors reserve the right to determine what we publish in this column.
- We do not wish to constrain expression or opinion, but we do wish to avoid overt commercial endorsement or political partisanship.
- We will include the op-ed author's email address as a means of stimulating meaningful dialogue with readers. As such, we will include the following footnote to that effect: "Readers wishing to comment on this piece are invited to contact the author (email) and/or the editor in chief (email)."

Our first op-ed, by Michael Golay, professor of nuclear science and engineering at the Massachusetts Institute of Technology, concerns climate change and appears in this issue. He argues for a framework that has the potential to transition to a global low-carbon economy but requires government action, international collaboration, and political will. This is a challenge by any measure but, in my view, one worth taking on.

As always, your comments are welcome; please send them to me at rlatanision@exponent.com.



Guest Editor's Note



Robert C. Armstrong (NAE) is director of the Energy Initiative and Chevron Professor of Chemical Engineering at the Massachusetts Institute of Technology.

The Challenges of Meeting Energy Demands in Environmentally Responsible Ways

Growing global energy demand, driven by population growth and rising standards of living in developing countries, suggests a global appetite for energy in 2050 roughly double that of today. At the same time, the IPCC Fifth Assessment (IPCC 2013) points out the urgency to reduce the carbon footprint of the global energy system. The dual challenge is thus to both double global energy supply by midcentury and simultaneously reduce carbon emissions.

Although climate change is the major environmental impact of the current energy system, attention is increasingly focused on the system's water and land impacts. There are complex interactions between energy and land, air, and water. For example, water is needed for many forms of energy production, (e.g., for fracking in shale gas production and for cooling in thermal power plants) and conversely energy is important in producing clean water (e.g., for desalination operations and for pumping to places where water is needed).

Articles in this issue of the *Bridge* look at some of the key coupled energy-environment challenges, examining impacts of energy processes on climate change, water use, and land use, as well as technologies that are likely to be critical in efforts to meet growing energy demands in a carbon-constrained world. Of particular interest are biofuels, especially for transportation, and solar and nuclear energy for electricity production.

The issues of interlocking energy, economic, and environmental systems are framed in the first paper, by John Reilly. He shows model predictions of projected energy demand growth and impacts on global and regional temperature increases, land use, and water stress if current trends continue. New science, technology, and policies are needed to transform today's energy system to meet human economic needs as well as to protect the environment. As he points out, energy demand growth will be greatest outside of the developed world.

Robert Jackson, Pierre Friedlingstein, Josep Canadell, and Robbie Andrew take a more detailed look at impacts of greenhouse gas (GHG) emissions on rising global mean temperature, assessing what it would take to limit that rise to 2–3°C. Looking at overall CO_2 (and equivalents) in the atmosphere, they examine different scenarios of CO_2 emissions reduction—a switch to renewables, carbon capture and storage (CCS)—to estimate when the CO_2 emissions budget for the 2°C and 3°C targets will be reached. Their article certainly underscores the urgency of action.

Adam Brandt and Gabrielle Pétron survey natural gas opportunities and issues. Natural gas is recognized as a national and global resource that can play a special role in a transition to a low-carbon future (MIT 2011): it offers the triple opportunity to lower carbon emissions (particularly in the electricity sector), enhance energy security, and stimulate economic growth. But there are also concerns about potential negative impacts of its production and distribution, particularly methane leakage and risks to water supplies. This article focuses on the first of these two concerns, with a careful review and analysis of fugitive emissions and air quality impacts. Solutions to minimize such emissions are necessary to enable the full benefits of natural gas resources.

Transportation accounted for about 27 percent of total energy use in the United States in 2013 (EIA 2015, p. E-2), dominated by liquid fuels, primarily petroleum products. The two leading options for fuel replacement in this sector appear to be renewable liquid fuels, such as those derived from biomass, or electrification of the transportation system, complementing ongoing energy efficiency improvements in the vehicle fleet. Chris Somerville and Stephen Long discuss opportunities for biofuels in the energy mix, with a focus on liquid transportation fuels, where such alternatives offer considerable convenience and familiarity for consumers. The authors describe the major sources of liquid biofuels and technologies for conversion, and then discuss their climate (net GHG emissions), land, and food impacts. A particularly intriguing option is advanced biofuels with CCS, which might be carbon negative.

Solar energy is the zero-carbon technology that has the largest upside in scale and thus is likely to play a key role in 2050 and beyond in the presence of carbon constraints. Much progress has been made in recent decades in reducing costs of solar electricity, but it is still more expensive than fossil-generated electricity in the absence of a carbon price. Nathan Lewis and Daniel Nocera (NAS) review the state of solar energy technologies such as photovoltaics, concentrated solar thermal power, and solar-to-fuel technologies. As they show, all of the technologies have made impressive progress, but interesting research and development challenges remain.[1] A very important area addressed in their article is the use of solar energy to produce fuels, which could provide the very long term, large-scale storage that a solar-dominated energy system would likely require. Finally, they discuss the ability to make transportation fuels with reduced carbon dioxide, an approach that offers the intriguing possibility of "renewable gasoline" down the road.

Another way to firm the electricity system in a world dominated by intermittent renewables is nuclear power. An important aspect of this source of zero-carbon electricity is global experience with nuclear energy at scale. Brittany Guyer and Michael Golay examine the economic and regulatory conditions needed to foster renewed growth of nuclear power in the United States. Together with cost, safety, and waste disposal considerations, they make the case for federal support as key to the expanded use of nuclear power.

The articles in this issue clearly just scratch the surface of important energy-environment interactions as we work to meet the ever increasing needs of humanity for energy, food, and water; but I believe they capture the nature of the problems that must be addressed to be successful in reducing carbon emissions while ensuring adequate energy around the world.

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[1] More information on solar-to-electricity technologies, costs, system integration issues, and needed research and development is in the recently released *Future of Solar Energy* study (MIT 2015).

Global development and population growth are projected to seriously stress natural resources and alter the climate as soon as 2050.

Impacts on Resources and Climate of Projected Economic and Population Growth Patterns

John M. Reilly is a senior lecturer in the Sloan School at the Massachusetts Institute of Technology and codirector of MIT's Joint Program on the Science and Policy of Global Change.

John M. Reilly

Global economic and population growth are driving energy, land, and water use, and there are complex connections between the use of these resources and the world's climate and natural environment.[1] A significant engineering challenge is to develop and deploy technologies that reduce human impact on the environment and make better use of resources while remaining robust in the face of unavoidable environmental change. Without significant changes in resource use patterns, projections indicate that fossil fuel use will continue to rise, more land will be converted for crops, and water stress will increase in many areas already subject to water shortages.

Even in the absence of climate and environmental change, these trends would lead to stress on water resources and natural systems as well as temperature increases of 3°C to as much as 8°C depending on the region and climate sensitivity. Higher global temperatures would be associated with an overall

[1] This paper draws on data and simulations from the MIT 2014 Energy and Climate Outlook. Complete data tables and figures are available at http://globalchange.mit.edu/research/publications/other/special/2014Outlook. In addition to the author, contributors to the Outlook are Sergey Paltsev, Erwan Monier, Henry Chen, Charles Fant, Jennifer Morris, Andrei Sokolov, Jin Huang, Kenneth Strzepek, Qudsia Ejaz, David Kicklighter, Stephanie Dutkiewicz, Jeffrey Scott, Adam Schlosser, Henry Jacoby, Audrey Resutek, Jamie Bartholomay, and Anne Slinne, all with the MIT Joint Program on the Science and Policy of Global Change.

increase in global precipitation (because a warmer climate speeds up the hydrological cycle, meaning more evaporation and more precipitation), but water runoff in many already water-stressed areas could be reduced, contributing to further water stress, with consequences for energy and food production.

This short paper presents a review of several key aspects of current global development to quantitatively describe how economic development drives energy, land, and water use and how the use of these resources may affect climate and the availability of resources.

Introduction: The MIT Integrated Global System Model (IGSM)

The elementary linkage of energy, climate, and the environment is a function of human use (combustion) of fossil fuels, emitting carbon dioxide (CO_2), a radiatively active gas, and leading to warming of the planet. The warming is augmented by positive feedbacks such as reduced ice and snow cover and increased water vapor. The warming and general changes in the climate then have impacts on the environment.

That characterization of the problem seems fairly simple. Deeper knowledge of the issues—and potential solutions—requires a better understanding of the underlying drivers and complex connections (Reilly 2013). To that end my colleagues and I apply the Massachusetts Institute of Technology (MIT) Integrated Global System Model (IGSM), a computer simulation model that represents explicit processes of earth systems (ocean, atmosphere, land surface, and freshwater) as well as an economic component that represents resource use and depletion, technical change, economic and population growth, and demand, supply, and trade in goods and services (Prinn 2012; Reilly et al. 2013).

The intent is not to predict what will occur but to give an idea of what is likely based on current givens. To the extent that the outcomes are undesirable, the scenarios presented can indicate what must be done—the engineering and technical challenges—to redirect growth and resource use for more sustainable or green growth.

Our projections incorporate key elements of existing policies and measures to which countries have committed in (as yet insufficient) attempts to stabilize the planet's climate, including the emissions targets in the Copenhagen-Cancún pledges agreed under the United Nations Framework Convention on Climate Change (UNFCCC) (UN 2009, 2010). These pledges focused on targets for 2020, which we extend through 2100, the horizon of our study. We include reductions beyond 2020 for the European Union (EU) to reflect targets proposed in its Emissions Trading Scheme (EU 2013), representing these targets by reducing the cap on emissions from power stations and other fixed installations by 1.74 percent every year.

Economic and Population Growth

Economic and population growth are key drivers of resource use, which can be moderated by both technical progress that enables more efficient use of resources and price changes that drive further conservation and efficiency measures.

Methodology

For expository purposes, we define three broad categories of countries based on their economic and population growth: *Developed*; an approximation of *Other* G-*20* nations; and the *Rest of the World (ROW)*.

Developed countries and regions are Australia, Canada, the European Union plus Switzerland, Norway, and Iceland, Japan, New Zealand, and the United States. The *Other* G-*20* countries comprise several large economies that have made rapid progress toward development in recent years, including China, India, Brazil, Mexico, Russia, and several rapidly growing Asian countries. We use the G-20 designation to recognize the growing importance of these additional countries to the global economy, but because our regional modeling does not allow us to aggregate to the exact G-20 group we also include Malaysia, the Philippines, Singapore, Taiwan, and Thailand, which are part of our "Dynamic Asia" region.[2] G-20 members Argentina, Saudi Arabia, South Africa, and Turkey are included in our *ROW* group because we don't separate them from broader regional groups, shown in figure 1.[3]

Findings

Underlying the economic scenario are population projections drawn from the UN's 2012 Revision (UN

[2] The actual members of the G-20 are Argentina, Australia, Brazil, Canada, China, the European Union, France, Germany, India, Indonesia, Italy, Japan, the Republic of Korea, Mexico, Russia, Saudi Arabia, South Africa, Turkey, the United Kingdom, and the United States.

[3] The underlying projections at this level of disaggregation are from the 2014 Energy and Climate Outlook (see footnote 1).

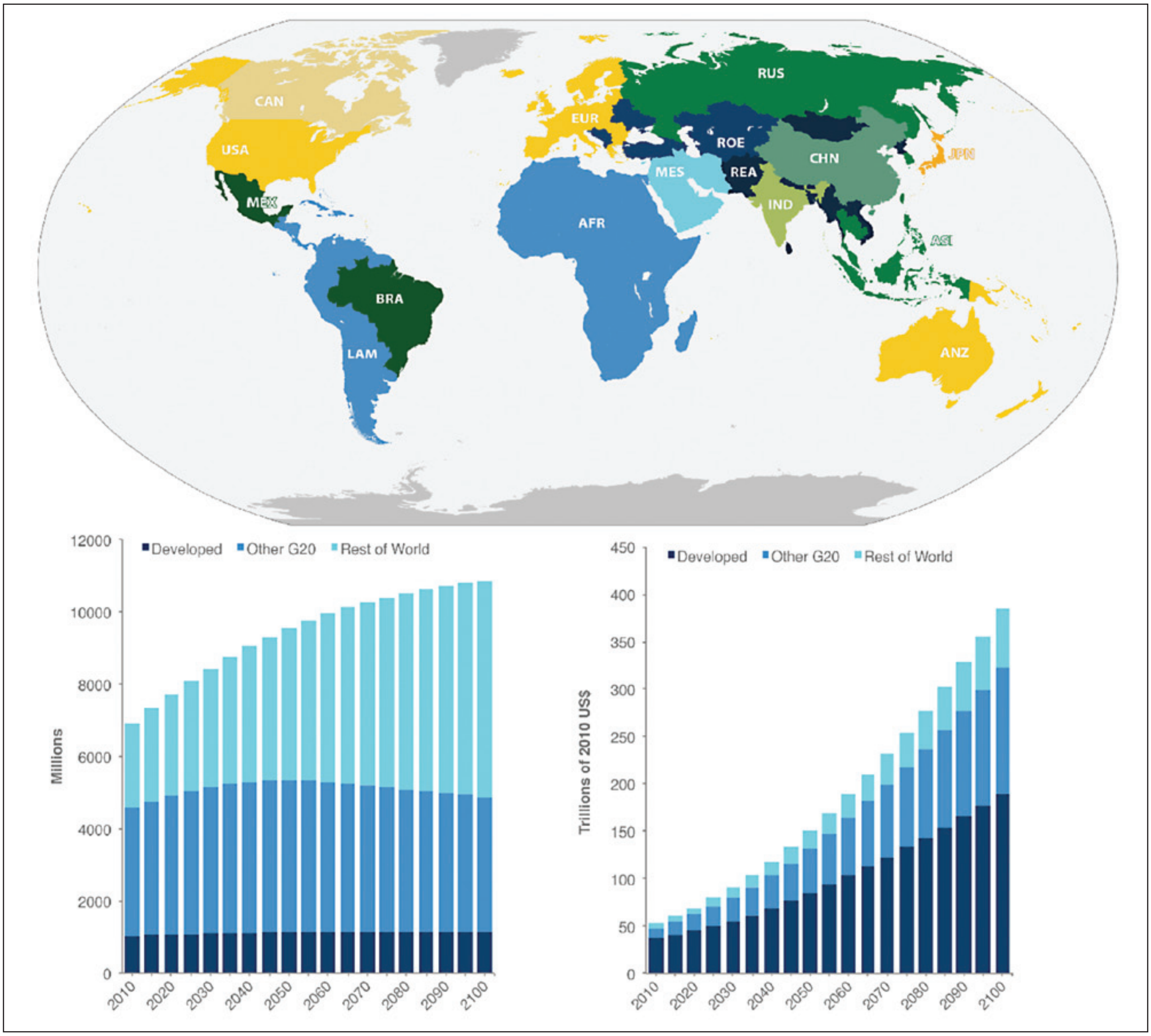

FIGURE 1 Regions of the MIT Integrated Global System Model (IGSM), population, and gross domestic product (GDP). The regions shown in the map are aggregated into 3 broad country groups: *Developed* countries (in yellows); an approximation of *Other G-20* nations (greens); and the *Rest of the World* (blues), for all of which we report forecasts for population (bottom left) and GDP (bottom right). By 2050, the *Developed* region accounts for 56% of GDP, evaluated at market exchange rates in the base year of the model, and only 12% of the population. ANZ = Australia & New Zealand; ASI = Asia; LAM = Latin America (not including Brazil); MES = Middle East; REA = other East Asia; ROE = rest of Europe. Sources: Population estimates are from UN (2013); GDP and all other projections and data are from the MIT 2014 Energy and Climate Outlook (see footnote 1).

2013), projecting a global population of about 9.5 billion by midcentury and 10.8 billion by 2100. Gross domestic product (GDP) growth is projected based on assessments of growth in the productivity of labor, land, energy, and endogenous savings and investment. These factors are more than enough to offset effects of resource depletion and other limits on natural resource availabilities.

Population assumptions show stable or declining levels in *Developed* regions, stabilization in the *Other G-20*, and continued increases in the *ROW*. By 2050 about 88 percent of the world's population will be in the *Other G-20* and *ROW*.

Productivity changes in the near term are adjusted to generate GDP growth projections, which are consistent with those of the International Monetary Fund

(IMF 2013) and similar to other long-term projections in that the *ROW* and *Other G-20* regions grow at a faster rate than the *Developed* countries. Even so, the disparity remains in terms of the fraction of economic activity, and declines only slowly.

In 2050 the *Developed* region will account for 56 percent of GDP (evaluated at market exchange rates in the base year of the model) and 12 percent of the population. However, that fraction of GDP is down from 71 percent in 2010. Evaluating GDP using a purchasing power parity (PPP) index would substantially upweight both current and future levels of economic activity in the *Other G-20* and the *ROW*, as well as their shares, compared with our use of market exchange rates (World Bank 2015). Absolute shares are subject to these caveats, but the more rapid growth we show for the *Other G-20*, as evident in figure 1, would be preserved if converted to PPP.

China is the largest economy in the *Other G-20*: it has been growing at around 10 percent per year or more over the past decade. Our forecast, consistent with internal projections in China, shows its growth slowing gradually to 3.0 percent by 2050. Even then, the *Other G-20* will outperform the other regions by a substantial margin.

Accounting for Regional Differences in Energy Consumption

An economy's energy consumption is a combination of household use, energy needed for infrastructure development, and energy used in the production sector. Our modeling framework has a full representation of depletable resources such as oil, coal, and gas; renewable resources such as land (which can be used to produce bioenergy in addition to conventional agricultural crops), wind, and solar; the technologies available to use these resources; and industrial and residential sectors that create demand for energy (Reilly et al. 2011). We further explicitly represent trade, because some low-energy or -emissions countries or regions may appear low in part because of large energy or emissions embodied in their trade.

Implicit in the representation of demand is a changing structure as economies become wealthier. In general, we see an energy-to-GDP elasticity of less than 1—that is, a 1 percent increase in GDP leads to a less than 1 percent increase in energy—in all regions, but it is much lower in heavily developed countries.

Many *ROW* members are still in the process of infrastructure development or cannot meet basic energy needs, hence more rapid growth in commercial energy demand relative to GDP. The *Other G-20* countries have more infrastructure development and are at a stage where income levels permit households to afford energy-intensive goods like private automobiles. Our projections show their economies growing rapidly.

These factors, in combination with differential emissions policies (e.g., more stringent in the *Developed* region), lead to the energy use projections shown in figure 2: flat or declining in the *Developed* region, rapidly growing in the *Other G-20*, and rising in the *ROW*. In fact, the *Other G-20* becomes an energy world of its own by 2050, with energy use as big as total global energy use today.

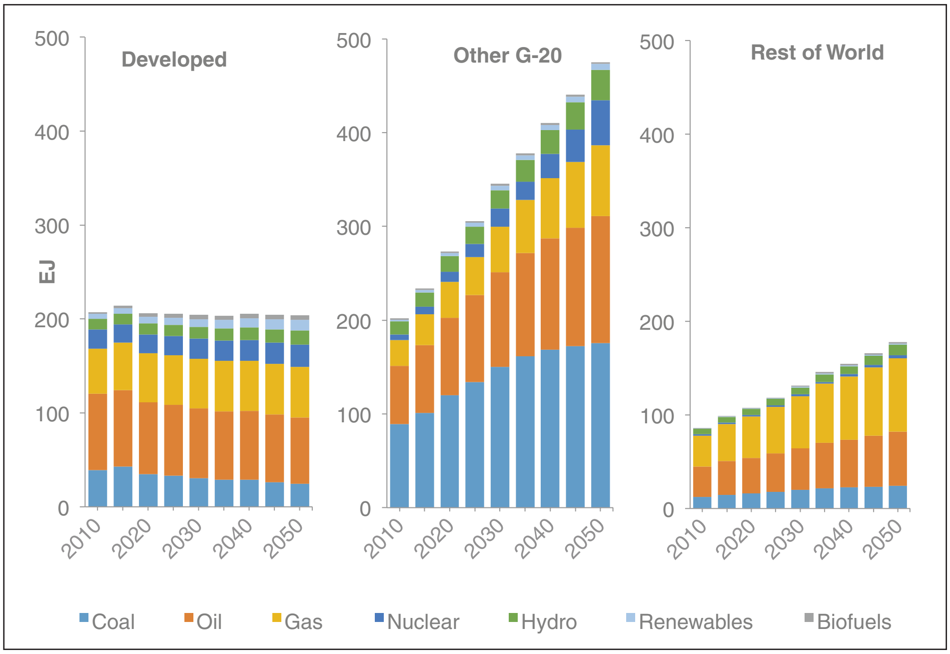

FIGURE 2 Primary energy use by major group, in exajoules (EJ), 2010–2050. We project flat or declining energy use in the *Developed* region, rapidly growing energy use in the *Other G-20*, and continued growth in the *Rest of the World*. By 2050, energy use by the *Other G-20* is as big as total global energy use today. See text for definitions of country groupings.

Emissions and Climate Implications

Total greenhouse gas (GHG) emissions from all sources of human activity—energy, industry, agriculture, waste, and land use change—are projected to reach 76 gigatonnes (Gt) CO_2-equivalent by 2050, and 92 Gt by 2100 if basic economic and policy drivers remain unchanged, nearly doubling from an estimated 49 Gt in 2010.

Sources of Emissions

Fossil fuel CO_2 emissions account for about two thirds of GHG emissions, basically unchanged throughout the forecast period, and about one third is from other sources. In 2050, CO_2 from fossil energy combustion will be about 49.9 Gt, CO_2 from cement and land use change roughly 7.6 Gt, methane about 12.5 Gt CO_2-equivalent, and nitrous oxide about 5.4 Gt CO_2-equivalent (other gases together will account for less than 1 Gt CO_2-equivalent).

Regional emissions reflect, to a large degree, regional energy use. The *Other G-20* countries are projected to contribute 43 Gt of emissions in 2050, of which 21 Gt will be from China and 11 Gt from India. The *Developed* region, because of policies in the Copenhagen-Cancún agreements, will emit just under 12 Gt, down from 14 Gt in 2015, while emissions from the *ROW* will have grown from about 13 Gt in 2015 to 22 Gt.

Emissions of long-lived GHGs combined with changing emissions of short-lived species (e.g., black carbon, sulfate aerosols, and their precursors; tropospheric ozone precursors) contribute to changes in concentrations of radiatively active species in the atmosphere. And they are in addition to the previous contributions to these concentrations, such as those of chlorofluorocarbons (CFCs), whose use has already been phased out but which remain in the atmosphere, and feedbacks from natural sources (or sinks) of carbon dioxide, methane, and nitrous oxide as they are affected by changes in climate or concentrations of the pollutants themselves.

Carbon dioxide concentrations are expected to reach about 530 parts per million (ppm) by 2050 and 750 ppm by 2100, with combined radiative forcing of all GHGs up to 5 watts/meter^2 (W/m^2) by 2050 and 7.3 W/m^2 by 2100. This is somewhat less than the highest scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) in its Reference Concentration Pathways (RCPs) (van Vuuren et al. 2011) and Special Report on Emissions Scenarios (SRES) (Nakicenovic

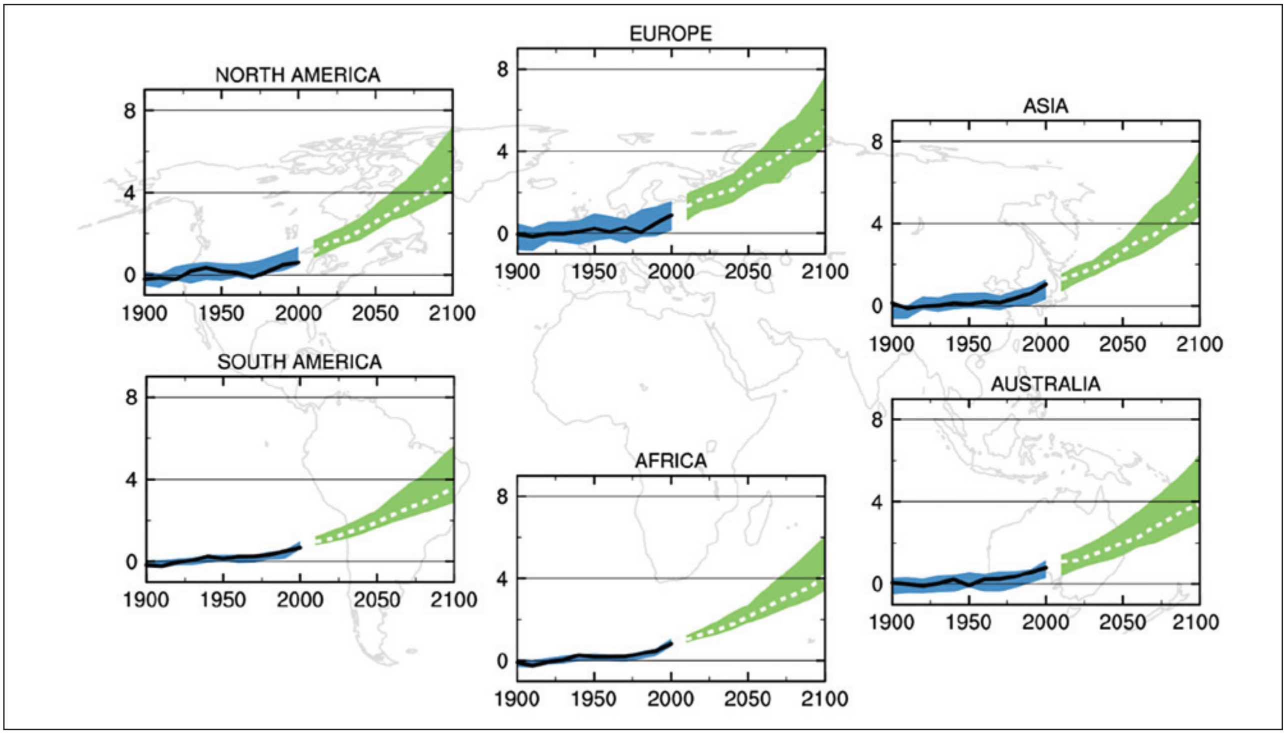

FIGURE 3 Regional temperature change, 1900–2100. Black lines represent observations; blue bands show the range of simulations over the historical period; white dotted lines show the mean of model runs, with five different initial conditions for the median climate sensitivity; green bands represent the range over all climate sensitivity scenarios and initial conditions for projections over the 21st century. All continents are projected to experience large increases in temperature.

and Swart 2000), which project 8–8.5 W/m^2 by 2100. But our projections remain above RCPs with policies that aim at stabilizing radiative forcing below 6.0, 4.5, and 2.6 W/m^2 through 2100.

The projections clearly show that the current path of development and policy efforts are both insufficient to achieve even a comparatively modest stabilization goal of 6 W/m^2 over the longer run.

Consequences

The environmental and climatic consequences of the projected levels of GHG and other pollutant emissions include changes in ocean acidification, temperature, precipitation, sea level rise, and vegetation. We take into account current knowledge of the global climate system response by sampling climate sensitivity (defined as the change in global mean temperature in response to a doubling of atmospheric CO_2 concentrations), using the 5th percentile (2.0°C), median (2.5°C), and 95th percentile (4.5°C) of its probability density function (see Monier et al. 2013).

In addition, in light of the large role of natural variability in projections of temperature and precipitation at the regional level (Monier et al. 2014), we use five different initial conditions for each climate sensitivity scenario in order to account for the uncertainty in natural variability. We show the range of mean surface temperature changes since 1900, along with projections for 2100, for six continental regions (figure 3).

All continents are projected to experience large increases in temperature by 2100: greater than 3°C in South America, Africa, and Australia and over 4°C in North America, Europe, and Asia. The range of projected warming is large (from 3°C to almost 8°C), indicating that there is considerable uncertainty in the projections, and this uncertainty increases over time. Nonetheless, there is also a good deal of certainty that future changes in temperature for all continents will be unprecedented.

Land and Water Resources

Changes in demand for different types of land are driven by growing population and changing consumption patterns over the forecast period. These supply and demand changes can be offset by technologies that improve yields over time and are resolved in markets through price hikes for commodities and resources. Higher resource prices can spur more intensive agricultural production practices in an effort to close imbalances.

Land Resources

The total land area of each of our three regions will remain the same, but its allocation to different purposes will affect the balancing of supply and demand both within regions and globally (figure 4).

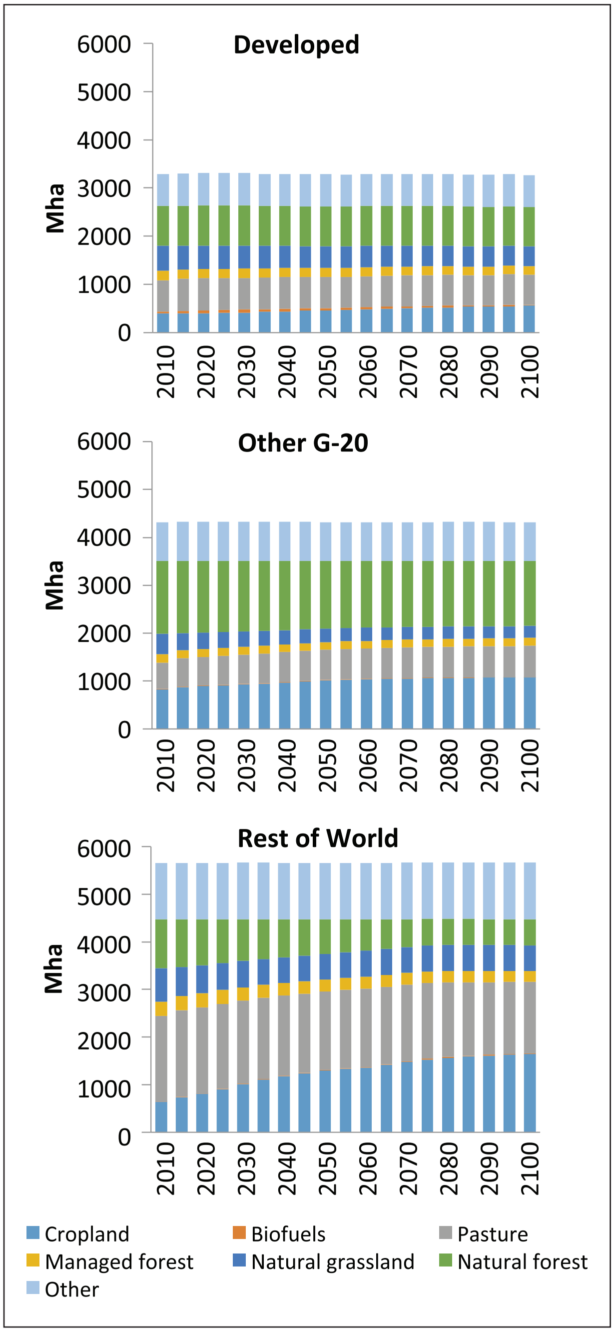

FIGURE 4 Land use by major group, millions of hectares (Mha), 2010–2100. All regions see some increase in cropland, but it is much greater in the *Rest of the World* as food demand rises faster in association with more rapid population growth and rising incomes. See text for definitions of country groupings.

Countries and regions exhibit not only a preference for commodities produced domestically but also differing willingness to convert unmanaged land to cropland, pasture, and managed forest; developed countries, for example, have forest and land protection policies in place and enforce them. This combination of forces gives rise to the regional patterns of land use change.

All regions see some increase in cropland, but it is much greater in the *ROW* as food demand is increasing faster due to more rapid population growth and rising incomes. With both the preference for domestically produced goods and greater willingness to convert unmanaged lands, there is more deforestation in these countries, as opposed to little if any in the *Developed* and *Other G-20* regions.

Food demand is increasing faster due to more rapid population growth and rising incomes in the developing world.

The pattern is quite different from that of energy use, where the biggest changes are in the *Other G-20*. This reflects the impact of the faster-growing population in the *ROW* on food demand, as opposed to the stronger effect of per capita income growth on energy demand in the *Other G-20*. Of course, deforestation is a source of CO_2 emissions when the biomass is burned or decomposes. This source of emissions is included in the MIT IGSM and in the projections discussed above.

Water Resources

Fresh water is a critical resource for the planet. The specific pattern of precipitation changes is highly uncertain and varies among climate models, but overall, and consistent with all global climate models, it is quite certain that with warming global precipitation will increase. The impact on freshwater resources will depend on how precipitation changes over land.

In our modeling we project the global annual amount of freshwater flow to increase by about 15 percent by 2100—and total water withdrawals for human uses to increase by about 19 percent. Water needed to maintain water-related ecosystems will increase by a similar amount. Much of the change in withdrawals will result from increasing economic activity and population growth, largely in tropical and subtropical developing countries, which are located primarily among the *Other G-20* countries and the *ROW*. Increases in water use rates tend to slow as per capita income rises (the income elasticity of water demand falls with income) and is near zero in highly developed countries.

To summarize the impacts of climate change and economic growth on water resources, we use a *water stress index* (WSI), defined as a ratio of total water requirements (municipal, industrial, energy, and irrigation) to freshwater flow (water from upstream sources and basin runoff). We further characterize our calculation as *potential water stress*, as our framework does not consider adaptation to changes in flow, which would inevitably occur. The index can take values from 0 (no water withdrawal requirements in the basin) to greater than 1.0 (the combination of growth and changing resources leads to water requirements greater than average annual flow). The water resource literature considers a WSI larger than 0.6 as indicative of severe water stress (Schlosser et al. 2014; Strzepek et al. 2013).

It may appear overly conservative that serious water stress conditions exist when as much as 40 percent of the annual freshwater flow in a basin is unused, but at least three factors must be considered: (1) most water basins have wet and dry seasons, and if 60 percent or more of the annual flow is being used shortages are likely during the dry season; (2) there is increasing concern about the downstream environment of water systems, with regulations or guidance on maintaining a minimum flow level to preserve freshwater systems that depend on river flows; and (3) most regions are subject to large interannual and even decadal variability in river flows, so using a large proportion of the average annual flow can create vulnerability during year-long or multiyear droughts (Smakhtin et al. 2005).

We map current stress and the change in water stress from 2010 to 2100 as estimated from our climate and economic projections (figure 5). Although our scenarios show reductions in water stress in some parts of North America, China, and the Middle East by 2100, the risk of water stress will increase in parts of India, China, Pakistan, Turkey, North and South Africa, and the United States, in many areas that are already stressed or severely stressed.

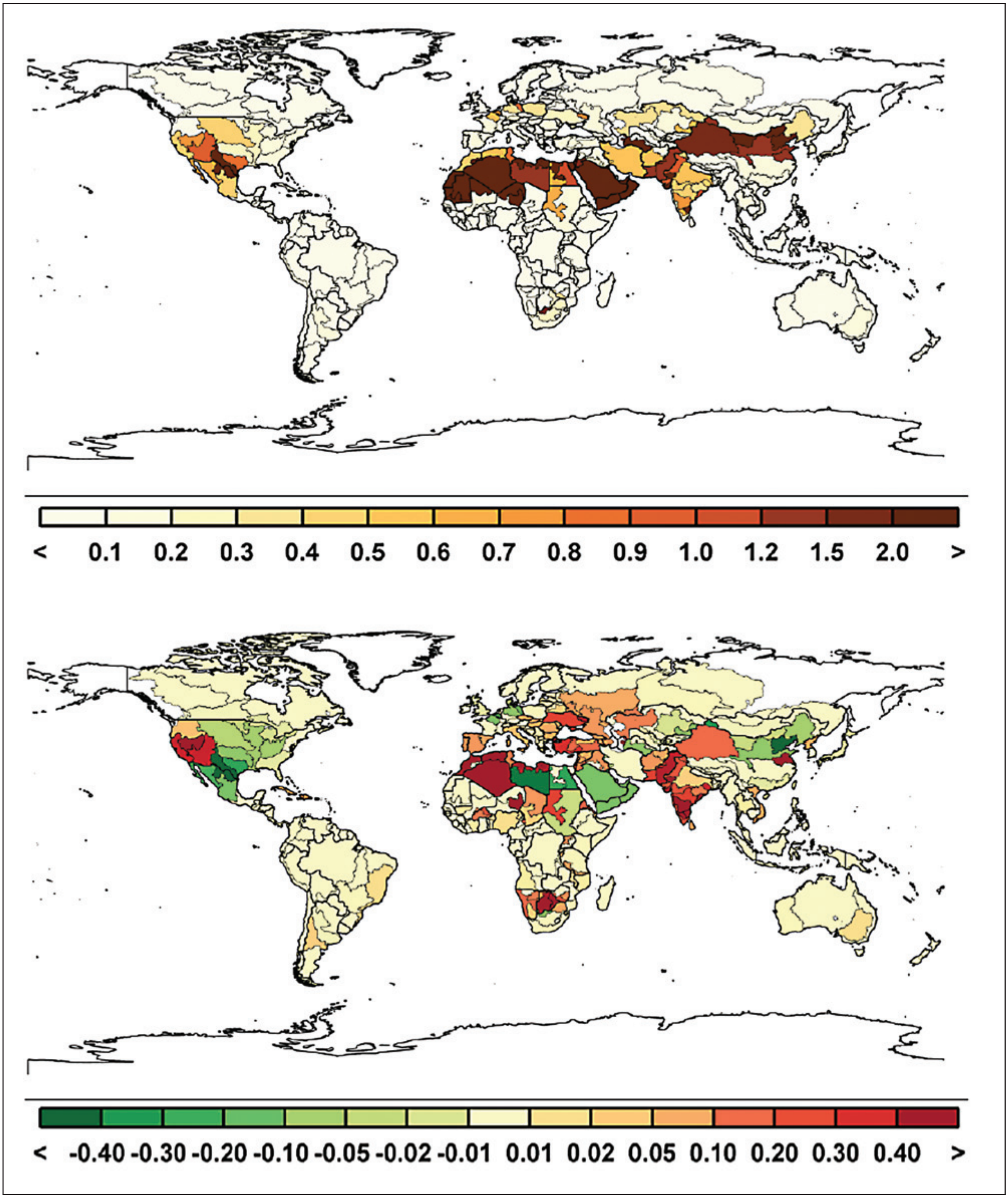

FIGURE 5 Water stress indices, 2010 and 2100. The top map index is the ratio of water demand to available annual flow. A ratio above 1.0 indicates either unsustainable demand met by depletable groundwater or unmet demands. The index in the bottom map is the difference between the top index calculated for 2100 minus the index for 2010. For the bottom map, oranges and reds show areas of increasing stress, greens show areas of decreasing stress. Many of the areas that show increased stress are already moderately or heavily exploited. Smakhtin et al. (2005) used the following designations: 0.3 ≤ WSI < 0.6 = moderately exploited, 0.6 ≤ WSI < 1 = heavily exploited, 1 ≤ WSI < 2 = overexploited (WSI = water stress index).

Engineering and Technical Challenges

Absent much stronger measures to reduce greenhouse gas emissions the world will see rising temperatures and changes in land use and water resources. The engineering and technical challenges involve inventing and improving on alternative energy technologies that produce low or no GHG emissions and scaling these technologies to meet global energy needs.

Engineering challenges involve inventing energy technologies to produce low or no GHG emissions and scaling them for global energy needs.

In 2010 renewable energy, including commercial biomass, wind, and solar, contributed only about 2 percent of global energy needs; nuclear and hydro contributed about 12 percent. Our projections show global energy use increasing more than 70 percent by 2050. There may be technical solutions to improve energy efficiency and perhaps slow demand growth, but persistent unmet energy needs outside of the developed regions of the world will at least partly offset efficiency gains.

To eliminate CO_2 emissions associated with fossil fuels, further electrification of the global economy is likely needed, but there is a long way to go to achieve this. To produce as much electricity as coal, oil, and gas did in 2010, renewable electricity would need to increase 16-fold from its 2010 level, and nuclear would need to increase 4.5-fold. There is potential for more hydro development in some parts of the world, carbon capture from large point sources such as coal or gas power plants is an option, and biomass energy could supply a substantial portion of the world's energy needs under the right conditions.

But each of these alternative energy sources faces technical challenges. Intermittent renewable electricity such as wind and solar must be integrated into the electric grid and supplies balanced to meet demand through either dispatchable sources of supply or energy storage. Despite significant efforts to make nuclear energy safe, combinations of human error (Three Mile Island, Chernobyl) and designs that were not resilient to extreme events (Fukushima) have undermined public confidence in these technologies and significantly increased costs. Hydropower resources are more limited and in some regions have been largely tapped out; but the bigger limit on development of this resource may be the ecological and social implications of large dams that flood unique natural ecosystems and extensive human settlements.

The development of cost-effective carbon capture and storage (CCS) has been elusive, with significant cost overruns at large-scale demonstration plants leading to cancellation of more extensive plans to develop the technology. If CCS were scaled up to capture a significant share of CO_2 emissions, a major transport system, likely involving pipeline, would need to be developed to get the CO_2 from points where it is produced to locations where it could be stored underground. With biomass energy, the dual concerns are excessive land use (and deforestation) and pressure on food prices if it uses a significant amount of the world's available cropland. If these challenges are not met there will be substantial warming and problematic changes in resources, as described in our simulations.

In addition to the concerns about land allocation and use, increases in water stress will require some combination of additional storage capacity in reservoirs, interbasin transfers of water, development of other sources of fresh water such as desalinization or recycling of grey water, greater efficiency in use, and ultimately the possible relocation or redirection of the growth of water-using activities toward river basins with adequate resources. Water scarcity is not the only potential problem. Changes in water temperatures would limit the use of water for thermoelectric cooling. And in areas where water scarcity is not a concern, the opposite problem of flooding may require engineering solutions to protect infrastructure.

It is widely recognized that mitigation (limiting GHGs) requires global cooperation and public policies that thwart private sector incentives to continue to burn cheap fossil fuels without capturing the carbon emissions. Greater public funding for research and development is likely needed, although directly pricing carbon could motivate private firms to undertake much of the development, demonstration, and scaling up of new low-carbon technologies.

Private firms and local and regional governments are already beginning to factor changing climate into their decisions. Failure to do so will affect their bottom lines and the cost of maintaining critical infrastructure.

Acknowledgments

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CO_2 emissions are rising at a rate that could raise global temperature 2°C above preindustrial values within about 20 years and 3°C by midcentury.

Two or Three Degrees

CO_2 Emissions and Global Temperature Impacts

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The world's energy mix is changing rapidly. Renewables such as wind and solar photovoltaics (PV) increasingly provide low-carbon, low-water, and low-air-pollution energy around the world (BP 2014). Denmark now generates 40 percent of its electricity yearly from wind power, and in Germany 20 percent of the country's electricity can be solar generated on sunny summer days.

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The rapid ascent of renewables is being driven by both policies and pricing. The European Union is on track to reduce greenhouse gas (GHG) emissions by one fifth in 2020 compared to 1990 levels, in part because of increased penetration of renewables and energy efficiency. California is similarly on course to cut its emissions to 1990 levels in the same time frame, a reduction of around 15 percent compared to business-as-usual scenarios. The levelized cost of electricity for wind and solar PV is already on par with fossil fuels and nuclear power in many markets around the world, in part because the prices of solar PV modules plunged three quarters from 2009 to 2014 and because the installed costs of utility-scale PV fell by one to two thirds (IRENA 2015).

Accompanying—and to an extent offsetting—the revolution in renewables is a parallel revolution in unconventionally mined fossil fuels. There is considerably more economically accessible oil and natural gas today than there was decades ago. The combined technologies of horizontal drilling and hydraulic fracturing increased US shale gas production from about 5 billion ft^3 (Bcf) per day in 2007 to more than 25 Bcf per day in 2014, now accounting for about 40 percent of total US natural gas production (EIA 2014). Similarly, production of shale and other unconventional oil drove US production to 9 million barrels per day in 2014, on par with the world's largest oil producer, Saudi Arabia (Jackson et al. 2014).

The balance of fossil and nonfossil fuels and the extent to which global energy use continues to grow will determine the Earth's future temperature. In this paper we place the current trajectory of carbon dioxide (CO_2) emissions in the context of both cumulative emissions since 1870 and *emission quotas*, the remaining emissions "allowable" to hold temperatures below a given threshold, in our case 2–3°C (3.6–5.4°F). In simple terms, the atmosphere can be viewed as a bucket that can hold a given amount of CO_2 before a particular temperature increase is reached. The amount in the bucket, plus the amount of CO_2 taken up by the oceans and lands, is considered the emission quota. We also compare emission quotas with the size of various fossil fuel pools available (through current technologies) and examine different pathways to keep temperatures from rising too far or fast.

Growing Global Energy Use and Fossil Fuel Emissions

Primary energy supply is increasing rapidly around the world, with a changing mix of fuels. From 2004 to 2013 global energy consumption rose 24 percent, from 9.7 to 12.7 billion tonnes of oil equivalents, driven primarily by increased demand in China and India (BP 2014). Coal use grew 50 percent during the decade (in large part because of growing consumption in Asia), compared with about 15 percent total growth for oil and 30 percent for natural gas. And the global share of energy supply from coal rose from 26 percent at the beginning of 2004 to 30 percent at the end of 2013, largely at the expense of oil, which declined from 37 percent to 33 percent of global energy supply (BP 2014). The shift to more coal and relatively less oil came despite declining coal consumption in the United States, Canada, and the European Union, among other nations and regions.

The European Union is on track to reduce GHG emissions by one fifth in 2020 compared to 1990 levels.

Rising Emissions

Notwithstanding the growing awareness of climate change in recent decades, GHG emissions have continued to rise. CO_2 emissions from fossil fuel burning and cement production in 2013 were 36.1 ± 1.8 billion metric tonnes (Gt), up 2.3 percent from 2012 emissions (35.4 Gt CO_2) and more than 60 percent from 1990 emissions (22.5 Gt CO_2) (Friedlingstein et al. 2014). Combined fossil fuel and cement emissions grew 1.0 percent per year during the 1990s but almost 3.0 percent annually since then, though with slightly smaller (2.5 percent) increases in the past few years.

One bit of good news is the near halving of CO_2 emissions from deforestation and other land use change (3.3 ± 1.8 Gt CO_2/yr on average) relative to the 1990s. Nonetheless, the world is moving toward GHG thresholds faster than anyone predicted in 1990, the reference year that the United Nations Framework Convention on Climate Change chose for climate change targets (UNFCCC 2006).

Calculus of Emissions and Global Temperatures

Emission targets are important because long-term global temperatures respond more or less linearly to cumulative CO_2 emissions, such as those from fossil fuel burning, cement production, and land use changes (Allen et al. 2009; IPCC 2013; Matthews et al. 2009; Peters et al. 2013). Cumulative CO_2 emissions were approximately 1,000 Gt between 1870 and 1980 and another 1,000 Gt between 1980 and 2013 (net global CO_2 emissions in 2013 were 40 Gt).

To have at least a 90 percent chance of keeping average global temperature increases below 2°C (3.6°F), global Earth system models (i.e., the most sophisticated climate models) suggest that cumulative emissions since 1870 need to be capped at no more than about 2,440 Gt CO_2 (figure 1) (IPCC 2013). If policymakers choose a riskier probability—say, at least a 66 percent chance of staying below 2°C for a cumulative threshold (table 1)—the allowable CO_2 emissions are some 500 Gt higher, about 2,900 Gt CO_2 cumulatively (figure 1) (IPCC 2013). (The 66 percent probability case comes with a one-in-three chance of the Earth's warming more than 2°C despite a capping of cumulative emissions at 2,900 Gt CO_2.) These emission thresholds are already close at hand because, as seen in figure 1, cumulative emissions from human activities totaled about 2,000 Gt CO_2 at the end of 2013 (roughly 75 percent from fossil fuels + cement and 25 percent from land use change; Friedlingstein et al. 2014; Le Quéré et al. 2014).

Figure 1 shows just how quickly the world is approaching thresholds for average global temperature increases of 2°C and possibly 3°C. For the 2°C scenario, the average growth in global CO_2 emissions since 2000 (2 percent/yr for fossil fuel, cement, and land use emissions combined) will carry the global temperature over that threshold just one decade from now in the 90 percent probability case and in two decades for the 66 percent probability case (figure 1, dashed red line). Zero percent growth (constant emissions at 2013 levels; black line) or a moderate emission decline of 2 percent/yr (dark blue dashed line) buys a few more years in the 90 percent probability case and a decade or two in the 66 percent probability case.

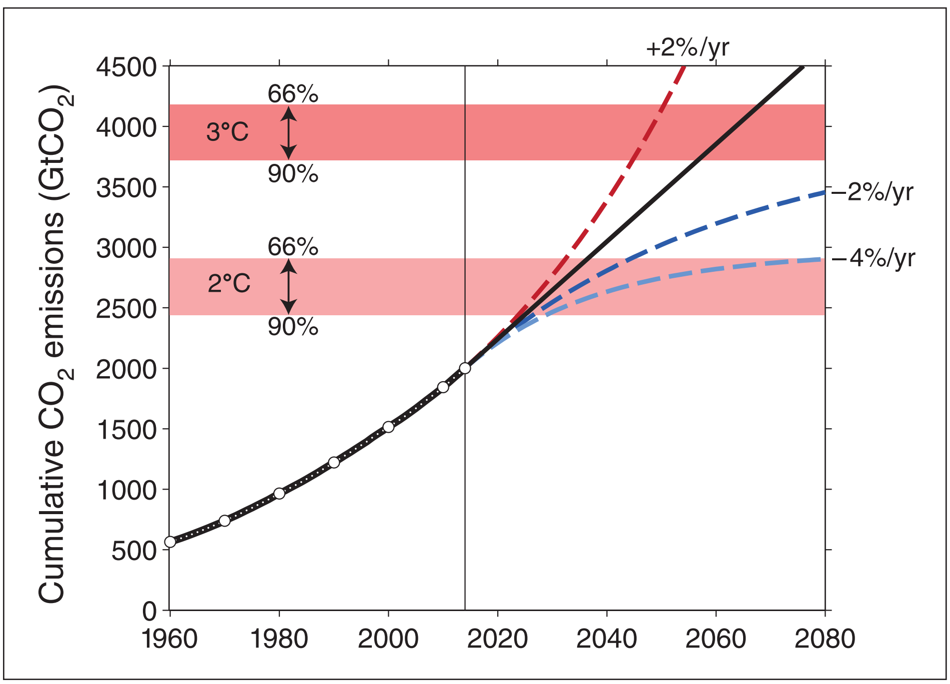

FIGURE 1 Cumulative global carbon dioxide (CO_2) emissions from fossil fuel combustion, cement manufacturing, and land use change from 1960 through 2013 (Le Quéré et al. 2014), plus four simplified future pathways: continued growth at the actual rate of +2%/yr observed over the past 15 years (dashed red line), constant 2013 emission rate (zero growth; solid black line), and mitigation at rates of −2%/yr (dark blue dashed line) and −4%/yr (light blue dashed line). Temperature threshold ranges for global average increases of 2° and 3°C (3.6° and 5.4°F) are from the IPCC (2013). The 90% and 66% probability cases refer to the likelihood of keeping global average temperatures below a given temperature if the cumulative emission threshold is not crossed (e.g., a 90% probability scenario for 2°C has a one in ten chance of having temperatures increase more than 2°C if cumulative emissions are capped at ~2,450 Gt CO_2 (bottom of the lower red band), whereas the 66% case has a one in three chance of having temperatures increase more than 2°C if cumulative emissions are capped at ~2,900 Gt CO_2.

In short, without immediate and substantial mitigation (e.g., 4 percent/yr; light blue dashed line in figure 1), time has nearly run out for 2°C mitigation (e.g., Stocker 2013). Such mitigation is possible but challenging, given the many-decade lifetime of existing power plants and other industrial infrastructure.

What is less well recognized is how fast global increases of 3°C (upper red band in figure 1) are approaching at current growth rates. For this higher temperature threshold, models suggest a total of about 3,700 and 4,200 Gt cumulative CO_2 emissions to have at least a 90 percent and 66 percent chance, respectively, of staying below a 3°C increase in

TABLE 1 Cumulative carbon dioxide (CO_2) emissions, measured in billion metric tonnes (Gt), remaining to have at least a 90% and 66% chance of staying below a 2°C and 3°C increase in global average temperature

	Cumulative CO_2 emissions (Gt) remaining by year			
	2°C		3°C	
	90%	66%	90%	66%
1980	1,450	1,900	2,700	3,200
2013	450	900	1,700	2,200

global temperature. The 2,000 Gt CO_2 already emitted at the end of 2013 thus indicates about 1,700 and 2,200 Gt CO_2 remaining for the 3°C scenarios.

How quickly either threshold is reached will depend, of course, on the trajectory of global CO_2 emissions. If they continue increasing at the average rate of 2 percent per year (red dashed line in figure 1), the 3°C threshold will be crossed in only 30 years (around 2045) for the 90 percent probability case and about 35 years (around 2050) for the 66 percent probability case. Carbon mitigation could lengthen them considerably (figure 1).

If emissions stay constant at the 2013 rate (figure 1, black line), the number of years to cross each threshold would be 11, 23, 43, and 55 for the 2°C (90 percent and 66 percent) and 3°C (90 percent and 66 percent), respectively. If emissions stopped growing today and remained constant at the 2013 rate of about 40 Gt CO_2/yr, the 90 percent and 66 percent thresholds would be crossed around 2055 and 2070, respectively. In contrast, if mitigation activities lead to an immediate global decline in CO_2 emissions of 2 percent or 4 percent per year (blue lines in figure 1), the 3°C threshold won't be reached at all in the timeline of our analysis (through 2080) and likely beyond.

Role of Fossil Fuel Reserves

Could the amount of carbon stored in fossil fuel reserves surpass the climate targets presented in figure 1? Based on global reserve data, the answer is clearly "yes" for temperature increases of 3°C and beyond.

Estimates of Reserves in 1980 and 2013

Proven reserves for oil and natural gas are greater today than they were decades ago, in spite of rapid growth in fossil fuel consumption and emissions. Table 2 shows that, in 1980, the global proven oil reserve was 683 billion barrels (BP 2014). From 1980 through the end of 2013, global oil consumption was a cumulative 884 billion barrels, about 30 percent more than the 1980 reserve estimate. Yet at the close of 2013 the proven oil reserve had grown to 1,688 billion barrels, almost 2.5 times larger than in 1980 and with a current reserve-to-production ratio of 53 years (BP 2014). Summing the 1980–2013 consumption and the most recent oil reserve estimate shows that actual proven oil reserves were 3.75 times higher than estimated back in 1980. Based on the continuing growth of unconventional oil production from shales, tight sandstones, and heavy sands, these reserves are almost certain to rise further in the future.

The history of proven reserves for natural gas shows a similar increase over time. The global proven reserve of natural gas rose from 72 trillion (10^{12}) m^3 in 1980 to 186 trillion m^3 at the end of 2013, an increase of

TABLE 2 Proven fossil fuel reserves in 1980 and 2013 for oil, natural gas, and coal, and their potential carbon dioxide (CO_2) emissions if fully used

	Proven fossil fuel reserves			
	Oil (billion barrels)	Natural gas (trillion m^3)	Coal (billion metric tonnes, Gt)	
1980	683	72	~1,100	
2013	1,688	186	892	
	Potential CO_2 emissions (Gt)			Total
1980	293	137	2,300	2,730
2013	725	355	1,865	2,945

Note: The fossil fuel reserves shown here do not include the larger set of probable and possible reserves. The potential CO_2 emissions from the total fossil fuel pool were larger in 2013 than in 1980 despite 1,000 billion metric tonnes (Gt) of total CO_2 emissions during the interval. For coal, 1 tonne = 10^3 kg.

160 percent (BP 2014). During the same period, natural gas production more than doubled, from 1.4 trillion m^3 per year in 1980 to 3.4 trillion m^3, a cumulative production of 78 trillion m^3. The sum of proven reserves in 2013 plus cumulative production from 1980 through 2013 therefore yields an actual proven reserve of at least 264 trillion m^3, 3.7 times the 1980 estimate (BP 2014).

Proven reserves of coal have not increased in recent decades but are nonetheless more extensive than for either oil or natural gas. The proven coal reserve in 1980 was approximately 1,100 billion metric tonnes (1 tonne = 10^3 kg); in 1993 it was 1,039 billion metric tonnes, and by the end of 2013 it declined 14 percent to 892 billion metric tonnes (table 2), roughly attributable to cumulative global extraction during 1993–2013 (121 billion metric tonnes) (BP 2014). Proven reserves in 2013 were sufficient for an additional 113 years at the 2013 global production rate (7.9 billion tonnes/yr).

Potential CO_2 Emissions from Reserves

Summing the carbon in proven reserves for natural gas, coal, and oil, there are some 3,000 Gt of potential CO_2 emissions if reserves are fully used. Based on conversion factors from the US Energy Information Administration,[1] the amount of potential CO_2 in the current natural gas reserve is 355 Gt CO_2, and for coal and oil the values are 1,865 Gt CO_2 and 725 Gt CO_2, respectively. These amounts total almost 3,000 additional Gt CO_2—more than enough to push cumulative emissions well past the 1,700 and 2,200 Gt remaining for the 3°C thresholds at 90 percent and 66 percent.

Importantly, the additional nearly 3,000 Gt of potential CO_2 emissions do not take into account several factors that will likely raise the total reserves available in the future. Because proven oil and natural gas reserves have been growing (table 2), it seems plausible that they will continue to do so. Moreover, the estimates used here are conservative as they do not take into account probable or possible fossil fuel reserves that have already been identified. McGlade and Ekins (2015) estimate that remaining fossil fuel resources are almost four times larger than the tally of proven reserves used here and may contribute 11,000 Gt of CO_2 emissions.

[1] The conversion factors are available at www.eia.gov/environment/emissions/co2_vol_mass.cfm.

Possible Mitigating Factors

Several factors beyond increased renewable energy could work to limit net CO_2 emissions even if fossil fuels are used. Considerable research is under way on the broad application of carbon capture and storage (CCS) technologies, which have the potential to store hundreds of Gt CO_2 if substantial technological and economic barriers can be overcome (e.g., Eccles et al. 2012; Haszeldine 2009).

Furthermore, negative emission technologies, defined as the deliberate removal of CO_2 from the atmosphere by technologies such as direct air capture of CO_2 or biomass energy coupled to CCS (Fuss et al. 2014), could permit larger emission quotas or the overshoot of emissions beyond a threshold if the future availability of those technologies were assured. But how effective such technologies might be, and how widely available they could become, is uncertain and depends both on technological developments not yet realized and on a high market price of CO_2 emissions.

Conclusions

Carbon dioxide emissions from human activities have grown substantially over the past decade, reaching about 40 Gt CO_2 per year in 2013 and some 2,000 Gt of cumulative CO_2 since 1870. Very high mitigation rates and sustained reductions in greenhouse gases are now required to have any chance of keeping global temperatures from rising less than 2°C compared to preindustrial levels. To date, however, such aggressive mitigation is not consistent with observed mitigation over the past 25 years or with current national emission reduction targets. Keeping global warming below 2°C also implies that the majority of proven fossil fuel reserves will stay in the ground, unless CCS techniques—unproven at the necessary scale—are rapidly implemented (McGlade and Ekins 2015).

Despite all the important global policy discussions to keep global temperature increases below 2°C, few people realize how quickly the world is approaching the cumulative emission threshold for an increase of 3°C. If global CO_2 emissions continue to grow at the annual rate of 2 percent observed for the past 15 years, increases of 3°C could be the reality only 30 years from now.

Stronger mitigation efforts are needed to reduce the rate of climate change, and adaptation policies are, and will be, needed to cope with the unavoidable climate impacts.

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Natural gas will be a useful alternative to coal and oil if fugitive methane emissions can be effectively monitored and mitigated.

Fugitive Emissions and Air Quality Impacts of US Natural Gas Systems

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Natural gas has many advantages as a fuel compared to coal and oil. It is abundant and can often be produced at low cost. It has significantly lower combustion emissions of numerous species including greenhouse gases, criteria air pollutants (e.g., carbon monoxide, ozone, sulfur dioxide), heavy metals, and acid-forming species (Moore et al. 2014). And with sufficient transmission and distribution infrastructure in the United States and other countries, it can be burned flexibly in sectors across the economy—power generation, industry, homes, and businesses.

In electricity generation the advantage of natural gas is clear. Natural gas turbines are pinnacles of engineering achievement: they consume fuel very efficiently and are capable of rapid adjustment in response to changes in power demand and supply.

Its advantages lead some to argue that natural gas could have long-term use in renewable-heavy power grids of the future. Recent experience in the United States is illustrative: the share of US electricity generated using gas rose from 18.8 percent in 2005 to 27.7 percent in 2013, mainly displacing

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coal (EIA 2015) and contributing to a 15 percent reduction in carbon dioxide (CO_2) emissions from power generation (EPA 2015a).

However, some problems remain with the use of natural gas. First, its combustion releases large quantities of CO_2 relative to zero-carbon electricity sources such as wind, solar, hydroelectric, and nuclear. Second, the production and processing of natural gas are not without air quality impacts. These impacts are associated with both the fuel consumption required along natural gas supply chain operations and the release of permitted or unintentional emissions of methane (the main constituent of natural gas) and other components of natural gas.

We briefly explain the mechanisms and risks of fugitive emissions, and then review recent assessments of such emissions at the national and local levels. Subsequent sections set out the implications of fugitive emissions for both local air quality and overall climate quality. We conclude with a summary of challenges in regulation and funding to protect air quality and maximize the potential benefits of natural gas as a reliable and abundant source of energy.

Fugitive Emissions: Causes and Risks

Natural gas can be lost from production, processing, and distribution systems through a variety of mechanisms. For a number of processes or pieces of equipment the operating conditions are designed to emit some natural gas; for example, some pneumatic controllers are powered using the pressure differential between high-pressure natural gas and the atmosphere, resulting in emissions upon each actuation of the controller (Allen et al. 2014a). In addition, numerous pieces of equipment have safety systems (e.g., pressure relief valves on tanks) that vent gas when out-of-specification pressure increases could pose danger to equipment and/or workers in the vicinity. Moreover, large quantities of natural gas can be released to the air from wells that unload liquids from the wellbore (Allen et al. 2014b) or from equipment that is "blown down" for maintenance operations. Last, natural gas can be lost from underdesigned and malfunctioning equipment (Brantley et al. 2014; IPCC 2000; Mitchell et al. 2015; Thoma et al. 2012).

Some loss of natural gas along the production and supply chain is likely unavoidable: perfection is not achievable in engineered systems, and most businesses face the reality of lost product. For example, packages are sometimes lost in complex delivery networks, and some fraction of electricity generated never makes it to consumers because of transmission line losses. In the natural gas system, product loss is a major concern because, even at relatively low loss rates, leaked natural gas poses climate and local air quality risks.

First, methane is a potent greenhouse gas. Assessed over a 100-year period, it is approximately 34 times more potent on a mass basis than carbon dioxide (IPCC 2013). With a global mean lifetime of about a decade, it has an even greater impact over shorter time periods—about 86 times more potent over 20 years (IPCC 2013). Factoring in the stoichiometry of combustion, each mole of methane not oxidized to CO_2 thus results in about 12 times the climate impact over 100 years—or 31 times over two decades.

Large portions of the US gas system are old, and some 3 million oil and gas wells have been abandoned.

Second, natural gas contains a variety of nonmethane species that can affect local air quality (Moore et al. 2014). Venting and fugitive emissions of natural gas result in the emission of volatile organic compounds (VOCs) present in the gas (some of them added; methanol, for example, is used as an antifreeze to protect pipelines) and can contribute to local surface ozone formation or smog (Edwards et al. 2014; Field et al. 2015; Gilman et al. 2013; Schnell et al. 2009). These and other hazardous compounds emitted from such operations (Helmig et al. 2014; Pétron et al. 2014; Thompson et al. 2014) risk affecting workers and/or nearby residents (McKenzie et al. 2012). The relative importance of these impacts depends on the natural gas composition, which varies among oil- and natural–gas producing regions and along the natural gas supply chain, as discussed below.

Current Understanding of Fugitive Methane Emissions

The US natural gas system comprises about 1 million producing oil and gas wells,[1] 300,000 miles of

[1] In 2013, 18 percent of US natural gas production originated from oil wells, according to data from the US Energy Information Administration, available at www.eia.gov/dnav/ng/ng_prod_sum_dcu_NUS_a.htm.

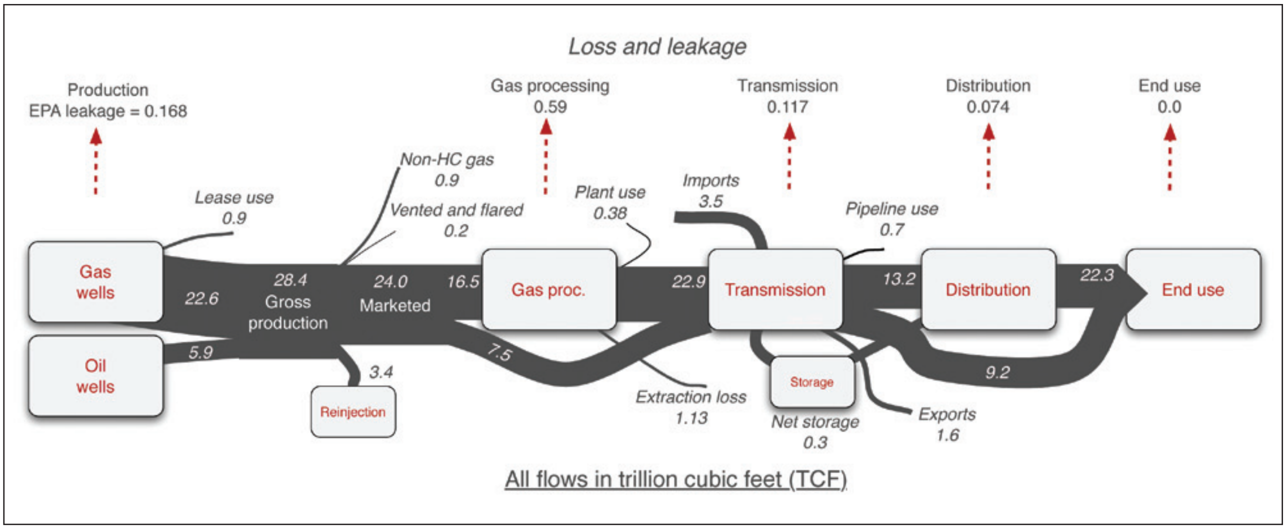

FIGURE 1 Flows in the US natural gas system, showing estimated loss from Environmental Protection Agency (EPA) inventory for year 2012. HC = hydrocarbon. Data from the US Energy Information Administration (various) and EPA (2014).

large-diameter high-pressure transmission lines, millions of miles of medium- and low-pressure distribution lines, and many tens of millions of points of connection (e.g., homes, businesses, factories) to the natural gas grid (EIA 2007; EPA 2015a). A diagram of natural gas flows and losses in the US gas system is shown in figure 1.

Large portions of the US gas system are old. Some 3 million oil and gas wells have been abandoned since the start of the US oil and gas industry in the late 1850s, many of them in unknown locations and sealed with outdated or nonstandard techniques (Brandt et al. 2014). Some cities, such as Boston and Washington, DC, have a large network of century-old cast iron gas distribution infrastructure, which has more leaks than modern systems (Jackson et al. 2014; McKain et al. 2015; Phillips et al. 2013).

Estimating Fugitive Emissions at the National Level

Emissions from the natural gas system are generally estimated using two quite different scientific methods. *Bottom-up* methods involve intensive and usually short-term study of the emissions of a representative set of equipment and facility types, the results of which are scaled up to a regional or national estimate of emissions using *activity factors* that represent the prevalence of a given activity or number of pieces of a given type of equipment. To take a simplified example, dozens of compressors might be surveyed for emissions using on-site detection and quantification equipment (Mitchell et al. 2015; Subramanian et al. 2015), and the resulting information used to generate an average compressor emissions factor that is then multiplied by the number of compressors in the country (Allen et al. 2013; Kirchgessner et al. 1996).

Alternatively, emissions from a region, state, or country can be estimated using *top-down* methods. These use in situ atmospheric chemical measurements in conjunction with meteorological data to estimate the flux of emissions behind the observed atmospheric concentrations. The two methods are illustrated in figure 2.

In the United States, fugitive emissions from the natural gas system are tracked through a nationwide "inventory" of emissions produced yearly by the Environmental Protection Agency (EPA 2015a). This inventory is based largely on bottom-up and engineering emission estimation methods and tries to account for control technologies used to reduce emissions (EPA 2015a, pp. A-126–A-389). Recent EPA national GHG emission inventories suggest leakage of about 1.5 percent of the methane in natural gas before it reaches consumers, with the most important points of leakage being production, transmission, and storage (Brandt et al. 2014).

A recent comprehensive review of experimental evidence found that methane emissions are undercounted in official EPA inventories (Brandt et al. 2014). A majority of experiments that measure methane emissions show excess emissions relative to inventory estimates at all scales, from equipment surveys to atmospheric studies integrating aircraft and tower data, and across the contiguous United States. The studies at the

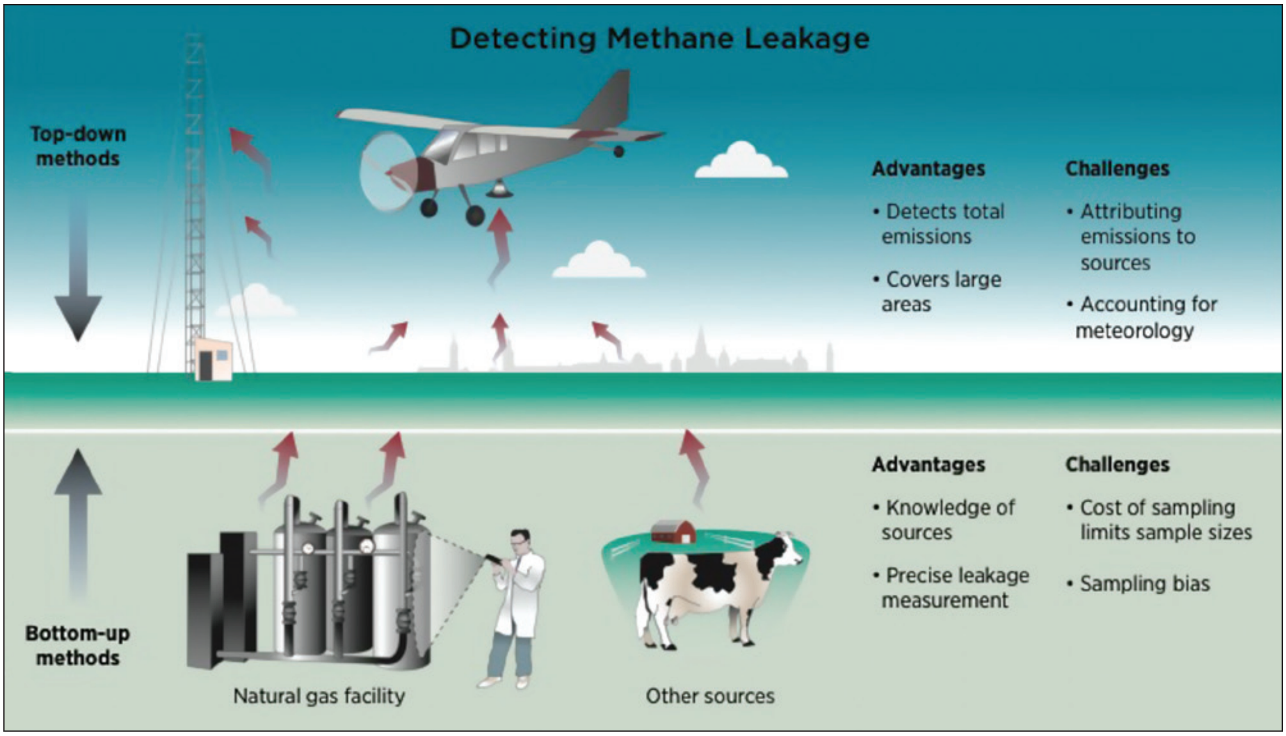

FIGURE 2 Illustration of top-down and bottom-up methods for detecting methane leakages. The advantages and disadvantages of the methods are complementary, suggesting important information to be gained from using both methods. Illustration by John Bellamy, Stanford University.

largest spatial scale suggest that national-level inventories undercount methane emissions from all sources by a factor of 1.25–1.75, which amounts to 7 to 21 teragrams per year of excess methane.

It is unclear how much of the national-level excess methane is due to the natural gas industry, but a variety of studies at regional, facility, and device scales suggest that official methods for counting natural gas emissions are underestimating methane emissions (Brandt et al. 2014). There is some evidence of undercounting in other methane source sectors as well, such as livestock in the north-central United States (Miller et al. 2013).

One challenge is that input data used in methane inventories are out of date: a dearth of funding and attention for many years means that many data are derived from limited-scale studies done in the early 1990s (Kirchgessner et al. 1996). Thankfully, with increased interest in natural gas fugitive emission rates spurred by the recent boom in US shale gas production, a number of studies have recently been completed or are under way. The largest effort, led by the Environmental Defense Fund in cooperation with industry participants (EDF 2013), involves independent scientists studying methane emissions from a variety of industry sources. US federal agencies, including the National Oceanic and Atmospheric Administration (NOAA) (e.g., Karion et al. 2013; Peischl et al. 2015; Pétron et al. 2012, 2014) and the National Energy Technology Laboratory (Skone et al. 2014), are also conducting important studies.

Understanding Variability in Regional Measurements

Recent atmospheric measurements by NOAA scientists have shown that oil and gas emissions of VOCs contribute significantly to local ozone production (Gilman et al. 2013) and are underestimated in state inventories (Pétron et al. 2014).

The recent NOAA studies have found substantial complexity in normalized natural gas emissions relative to production at the basin scale. For example, the Uintah basin in Utah and the Denver-Julesburg basin in Colorado show emission levels relative to production of 6.1–11.7 percent and 2.6–5.6 percent, respectively (Karion et al. 2013; Pétron et al. 2012, 2014). These are significantly larger than the EPA national average of 1.5 percent. In contrast, other producing regions, such as the Haynesville shale of Louisiana and Texas and the Marcellus shale in northeastern Pennsylvania, show emissions closer to the EPA estimates (Peischl

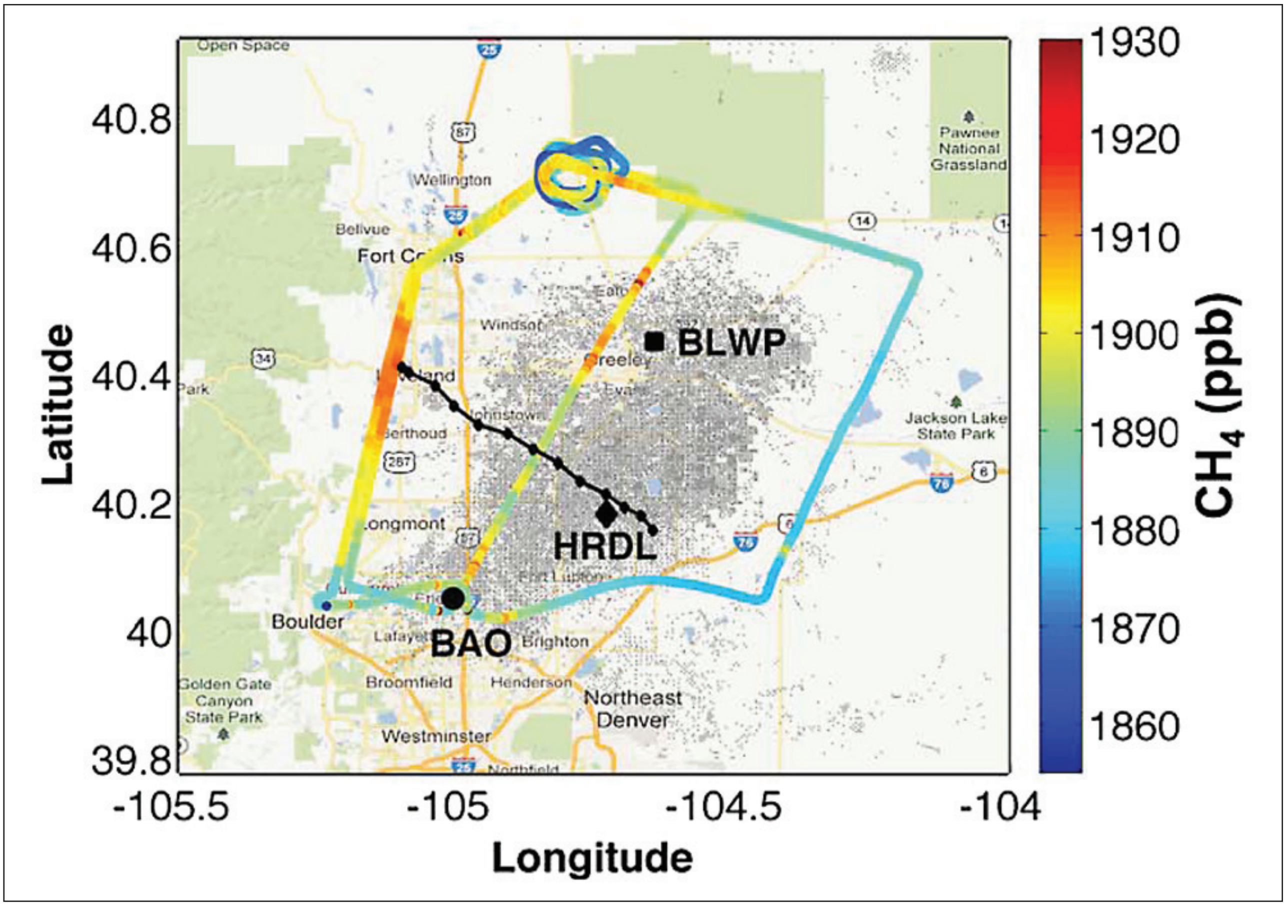

FIGURE 3 Example of a flight trace on May 29, 2012, showing upwind and downwind methane concentration differences in the Denver-Julesburg basin. These differences can be used with mass balance approaches to estimate emissions from a basin. The black line and dots show the mean back trajectory of the downwind air mass in the boundary layer; based on National Oceanic and Atmospheric Administration high-resolution Doppler lidar (HRDL) wind measurements from the Platteville site, dots are spaced 20 minutes apart. Grey dots show the locations of active oil and gas wells. The aircraft conducted a vertical spiral at the northernmost point of the flight track to derive the boundary layer height from trace gases and potential temperature vertical profiles. BAO = Boulder Atmospheric Observatory; BLWP = boundary layer wind profiler; CH_4 = methane; ppb = parts per billion.

et al. 2015). And atmospheric studies by other groups have found excess emissions in producing regions in California (Jeong et al. 2013, 2014) and in gas-consuming urban regions such as Los Angeles (Peischl et al. 2013; Wennberg et al. 2012) and Boston (McKain et al. 2015).

Differences in findings may also result from the method used to gather and/or analyze data. For recent top-down studies being performed by NOAA and affiliated groups, an instrumented airplane is flown on two transects perpendicular to the dominant wind direction, one upwind and the other downwind of the natural gas–producing region (figure 3). If meteorological conditions are favorable, a mass-balance approach can be used to differentiate quantities of methane exiting and entering the study region and estimate total methane emissions in the region. However, these studies typically have uncertainties of +/−30 percent, due mainly to variability and uncertainty in meteorological data such as horizontal wind speed and direction and boundary layer height, and may attribute methane emissions to different source categories.

Causes of confirmed different normalized emission rates among regions are generally difficult to discern. Possible drivers include the type of gas produced (dry versus wet), the type of operation (e.g., gas and liquid separation), and maintenance requirements (Zavala-Araiza et al. 2015). The Four Corners region[2] of the

[2] The Four Corners are the southwestern corner of Colorado, northwestern corner of New Mexico, northeastern corner of Arizona, and southeastern corner of Utah.

United States, for example, has the largest emissions of methane from liquid unloading associated with coal bed methane production (Allen et al. 2014b; Pacsi and Harrison 2015), which may partly explain why a European satellite identified the region as a methane hotspot on a 7-year average (Kort et al. 2014). In addition, the age of the infrastructure, maturity of the play, and regulations for emission controls and for leak detection and repair (LDAR) programs can factor into emission magnitudes and intensity.

There are also challenges in reconciling results from top-down and bottom-up methods. First, it is not clear how comparable a limited-duration sampling effort (involving one to ten aircraft flights, one midday flight daily) is to a yearly estimate of emissions generated by an inventory method. A variety of episodic emissions may or may not occur at a representative rate during the specific, limited times of the flights. Second, it is not clear that inventory methods based on bottom-up studies of devices are of sufficient sample size to detect and record the variety of rare but consequential emission events that can drive overall emissions from a source population.

Implications for Local Air Quality

The first major development of tight and shale gas (between 2005 and 2012) happened before federal regulations were updated to limit emissions of VOCs (and indirectly methane) from thousands of new small and distributed sources. Rapid oil and gas development in several states (Colorado, Pennsylvania, Texas, Utah, Wyoming) has occurred in rural or remote locations where little or no air quality monitoring was in place to document any changes in ambient levels of air pollutants.

Local ozone pollution in adjacent populated areas or in national parks or monuments has been one of the first triggers for some states to enact stronger emission regulations for oil and gas operations. For example, the northern Colorado Front Range, including the western portion of Rocky Mountain National Park, became a nonattainment area for surface ozone in 2007. The region is home to nearly 2 million people and over 20,000 oil- and natural gas–producing wells. To mitigate VOC emissions from both vehicles and oil and gas operations, the state of Colorado has some of the most stringent regulations in the country (CDPHE 2015).

As new, stricter oil and gas regulations (passed in spring 2014) are implemented, it will be crucial to independently assess the impacts of regulation on emission mitigation/reduction. Recently, the EPA, Department of Justice, and state of Colorado agreed on a settlement with Houston-based Noble Energy, Inc., resolving alleged Clean Air Act violations stemming from the operator's failure "to adequately design, size, operate and maintain vapor control systems on its controlled condensate storage tanks, resulting in emissions of volatile organic compound" (EPA 2015c). Regulation for emission reduction therefore needs to be done hand in hand with adequate technology design, field testing, installation, monitoring, and maintenance.

Another example comes from other Rocky Mountain regions. In the early months of both 2005 and 2006, surface ozone monitors in the Green River Basin of Wyoming showed levels above the EPA 2008 8-hour average air quality standard of 75 parts per billion by volume (ppbv).[3] Later, a team of NOAA scientists further documented rapid photochemical production of ozone during cold shallow surface temperature inversions in the basin (Schnell et al. 2009). Wintertime ozone pollution events were similarly reported in 2009–2010 (and in subsequent years) in the Uintah Basin in northeastern Utah, which was also experiencing a large boom

Atmospheric studies have found excess methane emissions in gas-consuming urban regions such as Los Angeles and Boston.

in oil and gas operations (Oltmans et al. 2014). Both basins are surrounded by mountains, so local emissions of ozone precursors, mainly driven by emissions from oil and gas operations, get trapped in a very shallow boundary layer during temperature inversions. With snow-covered ground, the sum of incoming and reflected sunlight in this shallow layer during the daytime feeds into the series of catalytic reactions that lead to rapid ground-level ozone formation.

[3] The final rule for the 2008 ozone standard was published in the *Federal Register* 73(60):16436–16514, available at www.gpo.gov/fdsys/pkg/FR-2008-03-27/pdf/E8-5645.pdf.

If ozone pollution mitigation remains a major driver for federal and state-level regulation of oil and gas sources, more work is needed to better understand sources, emissions, and short- and long-term ambient levels of hazardous air pollutants, which can affect the health of both workers and nearby residential communities. Esswein and colleagues (2012) documented workers' exposure to respirable crystalline silica during hydraulic fracturing operations. Field and colleagues (2015) showed that a treatment and recycling facility for produced and flowback water from fracking operations was responsible for enhanced levels of air toxics (toluene and xylenes) in the Pinedale Anticline gas field of Wyoming. And analysis of aircraft data showed that benzene emissions from oil and gas operations in the Denver-Julesburg Basin appear to be much larger than anticipated by the state inventory calculation (Pétron et al. 2014) and warrant a thorough investigation of important hazardous air pollutant source vectors and exposures.

Implications for Climate Benefits of Natural Gas

A comparison of the impacts of substituting natural gas for coal or transportation fuels such as gasoline and diesel indicates the possible climate benefits of using natural gas. Updated results from this comparison, using the most recent IPCC global warming potentials and taking into account a recent upward revision in methane's heat-trapping capacity (Myhre et al. 2013), suggest that methane leakage must be at or below 2.7 percent if natural gas substitution for coal-fired power is to have climate benefits over all timescales (Alvarez et al. 2012). For benefits over a century-long timescale, leakage could be as high as 6 percent.

Given these targets and the current understanding of excess leakage, the substitution of natural gas for coal may not be beneficial immediately but should have robust benefits over a 100-year assessment period (Brandt et al. 2014). But as a substitute for gasoline or diesel the breakeven leakage rates are much narrower, making climate benefits from such a switch unlikely over even century-long timescales.

Solving the Problem

Can the problem of fugitive methane emissions from the natural gas system be solved? Numerous studies point to cost-effective means to reduce methane emissions (e.g., Harvey et al. 2012; ICF International 2014). Some solutions involve replacing a device or component with an improved version (e.g., replacing high-bleed pneumatic devices with low-bleed models, or capturing gas from centrifugal compressor seal leaks). Other cost-effective options are management shifts; for example, the implementation of formal LDAR processes at compressor stations was found to be very cost effective (ICF International 2014).

Because reducing leakage increases the quantity of salable product, there are economic benefits to emission and leakage reduction in addition to the goals of safety, environmental compliance, and social license to operate. One key challenge is that losses tend to be dispersed across a great variety of equipment types, and often a small number of leaks (called *superemitters*) are responsible for a large fraction of the total emissions.

Federal and private funding is being brought to bear on the problem of the expense of methane leak detection. Efforts in this area would greatly lower the cost and increase the effectiveness of the currently labor-intensive, and for some sources limited, leak detection process (ARPA-E 2014; EDF 2015).

Federal regulations (adopted in 2012 and later amended) address emissions from thousands of new gas wells (including sources such as gas well completion flowback and tank emissions) and call for upgrades to low- or no-bleed pneumatic devices (EPA 2015b). Existing wells and small gathering compressors are under the purview of states and emission reduction regulations vary greatly from one state to the next. In the Rocky Mountain region, Colorado, Wyoming, and Utah have implemented the most stringent emission control and LDAR programs for counties that violate federal ozone standards. More uniform standards and generally adopted tracking methods would both help to ensure consistent data and inform effective measures across jurisdictions.

To track progress, it is critical that states with existing and/or growing oil and gas operations maintain adequate ambient air quality monitoring and field operation inspections to preserve air quality for local populations and/or protected areas. Adequate funding and staffing are essential to ensure local capacity to investigate and monitor air impacts of current and future oil and gas operations.

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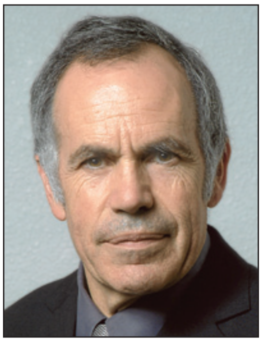
As truly renewable fuels, advanced biofuels and sugarcane ethanol offer energy security far into the future.

The Future of Biofuel and Food Production in the Context of Climate Change and Emerging Resource Stresses


Chris R. Somerville


Stephen P. Long

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Approximately 10 percent of energy use worldwide is derived from direct or indirect combustion of biomass, providing as much energy as hydro, geothermal, solar, and wind combined.

Energy produced by combustion of biomass or biomass-derived compounds is *bioenergy*, of which liquid biofuels are a small subset. In 2013 some 110 billion liters of biofuels were produced worldwide. About two thirds of the volume was ethanol produced by fermentation of sugars from corn and sugarcane, and one third was biodiesel, mostly fatty acid esters from vegetable oils (IEA 2015).

Approximately 21 million hectares (Mha) of land were used for production of biofuels in 2010 (Langeveld et al. 2014), about 1.4 percent of the 1.5 billion Ha currently used for crop production. Most of the biofuels were produced in the United States and Brazil, but 60 other countries have implemented biofuel mandates or goals (Lane 2013). The projected expansion of biofuel production at 2.7 percent per year from 2010 to 2040 (EIA 2014) implies an increase in the amount of land allocated to them rather than to food, feed, or ecosystem services. Given estimated population growth and

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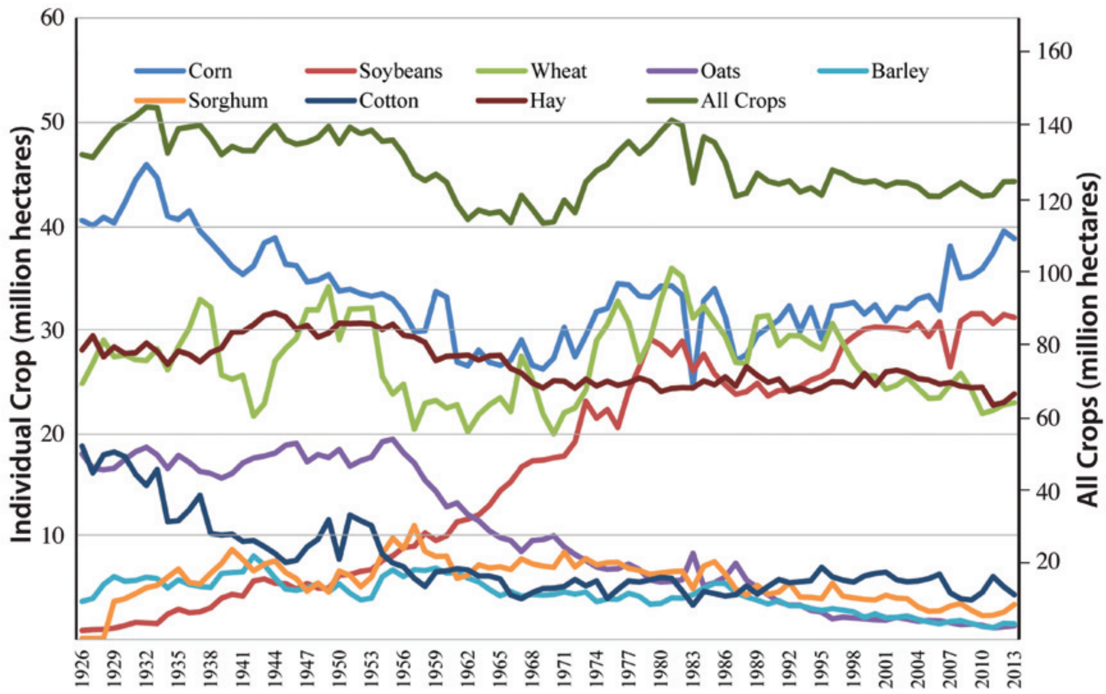

FIGURE 1 Millions of hectares planted with the eight major US crops (barley, corn, oats, rice, sorghum, soybeans, upland cotton, and wheat), 1926–2013. Soybeans are grown as a protein source; a small amount of neutral lipid is a byproduct used for both food and biofuel. Adapted from Wang et al. (2014).

possible threats to biodiversity and ecosystems, some believe that public support for the use of biofuels is misguided. At the same time, concern about climate change has stimulated interest in the development and deployment of technologies for biofuel production to reduce net carbon emissions from the use of liquid transportation fuels.

We outline some of the issues that frame the public discourse of these subjects and offer a view of the possible trajectory of biofuels. We focus largely on the United States and Brazil, which currently have the most experience, production, and use.

Corn Ethanol

In 2006–2010 about 30 percent of the US corn crop was used for ethanol production (table 1). About two thirds of the mass of corn kernels is starch, which is depolymerized to sugar and fermented to ethanol; the remaining third, a nutritious high-protein residue termed *distillers dried grains*, is fed to animals. Most of the corn ethanol produced in the United States is

TABLE 1 Changes in US corn yields and destinations, 1990–2010

	1990–1994	2006–2010	% increase
Yield per hectare (ha)	7.5 t ha^{-1} yr^{-1}	9.7 t ha^{-1} yr^{-1}	29.3
Price	\$128 t^{-1}	\$198 t^{-1}	54.7
Hectares	27.6 Mha	32.1 Mha	16.3
Total production	207 Mt yr^{-1}	311 Mt yr^{-1}	50.2
Uses			
Ethanol	11 Mt yr^{-1}	94 Mt yr^{-1}	854.5
Export	45 Mt yr^{-1}	54 Mt yr^{-1}	20.0
Feed and other uses	151 Mt yr^{-1}	163 Mt yr^{-1}	7.9
Dried distillers grain	4 Mt yr^{-1}	31 Mt yr^{-1}	854.5

Mha = million hectares; Mt = million metric tons; yr = year. Amounts of dried distillers grain are included as these are also used as animal feed. Numbers are averages of the two 5-year periods. Calculated from USDA-ERS (2013), USDA-NASS (2013).

mixed with gasoline to produce a 10 percent blend; small amounts are used to produce 85 percent blends or exported.

The amount of corn used for ethanol rose significantly during the past 15 years, as did the amount used for other purposes, including exports (table 1).[1] The rise in US corn production was due to three factors: (1) higher yield per acre, (2) unused land brought into production, and (3) the transition by some farmers away from less profitable crops. The small expansion (16.3 percent) in land area since the introduction of corn ethanol (table 1) is less than one quarter of the 17 Mha that have dropped out of overall US crop production since 1980 (figure 1; World Bank 2015), and even with the increase, the amount of US land in corn today is about 10 percent less than in 1930.

Sugarcane ethanol has a high ratio of net energy capture and contributes to an 82 percent reduction in GHG emissions.

Since the 1930s average US corn yield has risen about eightfold as a result of improved breeding methods, development of hybrid varieties, greater inputs of chemicals and fertilizers, and improved agronomy, including increased planting density. The higher yield per hectare has been achieved without an increase in the amount of nitrogen fertilizer, which has remained at 140 kg/ha^{-1} since the 1980s (Long et al. 2015a).

The rise in grain yield has been accompanied by increased production of crop residues and widespread adoption of minimum till agriculture, which may be beginning to cause reaccumulation of carbon in Corn Belt soils after years of decline (Bernacchi et al. 2005). But because the ratio of energy output to input for corn ethanol is about 1.6, net greenhouse gas (GHG) emissions are reduced 34–44 percent compared to those of petroleum-based fuels (Wang et al. 2012). The fermentation process produces nearly pure carbon dioxide (CO_2) that could be used directly for geological sequestration, resulting in a CO_2-negative or near-negative fuel (IPCC 2014).

Sugarcane Ethanol

The US Environmental Protection Agency classifies sugarcane ethanol as an "advanced biofuel" because of its greater than 50 percent net GHG reduction relative to gasoline. Brazilian sugarcane is the second largest source of ethanol (Youngs et al. 2015): Brazil grows approximately 9 Mha of sugarcane, of which roughly half is used to produce about one third of the world's sugar and the other half ethanol. Mills burn the *bagasse*, the solids that remain after extraction of the sugar, to produce energy for processing the sugarcane, and any surplus is exported as electricity to the grid. This bioelectricity production complements the use of hydro, which provides about 70 percent of Brazilian power.

Sugarcane ethanol has a high ratio of net energy capture and contributes to an 82 percent reduction in GHG emissions (Wang et al. 2012). Continued innovation—from crop production to processing of the wastes—promises to further reduce such emissions.

Brazil mandates that gasoline contain 27 percent ethanol, and pure dehydrated ethanol is also sold to retail consumers. Thus ethanol provides about 40 percent of the transportation fuel for the light-duty fleet, which is about 95 percent flexfuel and can use any mix of alcohol and gasoline. Gasoline is subsidized but ethanol is not; consumers purchase the gasoline:ethanol mixture or pure ethanol depending on the relative prices of gasoline and ethanol.

Most sugarcane ethanol is produced in the state of São Paulo, but expansion is planned for adjacent states in a low-productivity region called the Cerrado, which supports about 160 Mha of cattle ranching at very low stocking density. Sugarcane farming will likely expand through intensification of cattle ranching as the demand for biofuels increases (Somerville et al. 2010).

The Brazilian government estimates that as many as 64 Mha of land are suitable for sugarcane production without any negative impact on the Amazon forest or Pantanal regions. Such an expansion might enable Brazil to produce about 15 percent of the volume of liquid fuels that were consumed worldwide in 2014 (IEA 2015; Somerville et al. 2010).

[1] Demand has stalled since 2014 because less than 8 percent of US light-duty vehicles (~19 million) are certified to use more than 10 percent ethanol, so retail distribution outlets are generally unwilling to distribute higher blends.

Cellulosic Biofuels

FIGURE 2 Harvesting one year's growth of the perennial cellulosic feedstock Giant Miscanthus (*Miscanthus* × *giganteus*). Picture courtesy of the University of Illinois, Institute of Genomic Biology.

Approximately 70 percent of the body of a plant is a composite of structural polysaccharides, mainly cellulose and hemicellulose, which can be depolymerized with acids or enzymes to glucose or a mixture of sugars, respectively (Youngs and Somerville 2012). The remaining mass is mostly a polyphenolic material called *lignin*, with small amounts of protein, lipid, and minerals. The sugars that constitute the structural polysaccharides can be fermented by various organisms to produce fuels such as ethanol, termed *cellulosic fuels*.

The industrial yeasts that have traditionally catalyzed most ethanol production processes are fastidious and use only glucose. Recently, strains have been engineered to use the most abundant sugars derived from hemicellulose with high efficiency, and in 2013–2014 half a dozen small commercial-scale "cellulosic ethanol" biorefineries started operating in Brazil, Europe, and the United States (Youngs et al. 2015), using agricultural residues such as corn stover, wheat straw, and sugarcane bagasse as feedstocks. Residues from forestry operations are also suitable feedstocks for cellulosic fuel production. In all cases care must be taken to ensure that sufficient residue is left on the land to maintain soil carbon contents. Importantly, these cellulosic sources do not compete with resources needed for food production.

Advantages of Cellulosic Biofuels

The whole plant is used rather than just the fruits or tubers, maximizing efficiency of conversion of solar energy into fuels. In addition, feedstocks can be chosen on the basis of high productivity, low input requirements, and the ability to use land unsuited to the production of food crops. A recent survey identifies a number of highly sustainable perennial feedstocks for cellulosic fuels that could be grown on a wide range of lands, including semidesert and salinated soils where no food crops could be grown (Davis et al. 2014a).

Highly productive perennial grasses that produce soil-binding root mats can be grown on land that would be eroded by cultivation for annual food crops. They can also grow on soils too poor for the cultivation of food crops as they recycle mineral nutrients. One such candidate, *Miscanthus* × *giganteus*, showed no significant difference in yield when grown on high-quality or marginal land in Illinois (Arundale et al. 2013), and in England it was grown for 14 years without fertilizer, with no evidence of yield loss (Christian et al. 2008).

Perennial growth provides many advantages, including no replanting costs, faster spring emergence resulting in increased solar energy capture, recycling of nutrients, and the capacity to bind the soil with a year-round root and rhizome mat (Davis et al. 2014a; Heaton et al. 2008). Indeed, such crops could bring back into use the millions of US hectares abandoned from row crop use during the Dust Bowl in the 1930s. They can convert more sunlight energy into biomass energy per unit land area than food crops and require lower inputs (Dohleman and Long 2008). Furthermore, analysis suggests that, for the most productive of these species, such as *Miscanthus* (figure 2), increased soil carbon storage would completely offset the small amount of fossil fuel energy needed over their lifecycle (Dohleman et al. 2012; Wang et al. 2012).

Production Opportunities and Costs

For the United States, with a large underused land base, especially in the South, there is an opportunity to replace a significant portion of the country's liquid fuel use with cellulosic fuels without competing with food and feed crops (Davis et al. 2012, 2014a; DOE 2006; Heaton et al. 2008; Miguez et al. 2009; Somerville et al. 2010).

The use of plant-based biofuels could simultaneously reduce GHG emissions and achieve net removal of carbon from the atmosphere.

For example, the eastern US ecoregion, which receives sufficient rainfall to support bioenergy crops without irrigation, comprises 165 Mha, about 17 percent of the total area of the 48 contiguous states. But the entire region has been in agricultural decline since the settlement of the Midwest and the Civil War, such that today only 20 percent is in agriculture. This decline is ongoing: between 1986 and 2000, 12 Mha dropped out of row crop production (Loveland and Acevedo 2014)—enough land to support a major replacement of fossil fuel oil use. The use of this land for bioenergy crops could generate a perpetual source of liquid fuels that would offset a major portion of national GHG emissions or, combined with carbon capture and storage, even achieve net removal of carbon from the atmosphere while producing fuel.

The capital costs of lignocellulosic biorefineries are high relative to the value of the fuels produced, but will likely decline as the industry learns by doing. In the meantime, a potentially better option, especially for emerging economies, may be to convert lignocellulosic biomass to methane using anaerobic digesters, which are inexpensive to build and can use essentially any source of organic material. The gas can be used directly to generate electricity in inexpensive and robust reciprocating engine generators or cleaned and compressed for use as transportation fuel in suitably equipped vehicles (Bond and Templeton 2011).

Biodiesel

Ethanol is generally not a suitable fuel for diesel or jet engines, so an industry has developed around the use of fatty acid methyl esters, or derivatives, as "biodiesel."

Approximately 26 billion liters of biodiesel were produced in 2013 (BP 2014), most from triacylglycerol (TAG) produced as storage oils by plants such as rapeseed, soybean, sunflower, and oil palm. The conversion of such lipids to fuels is simple and inexpensive to implement at any desired scale. Using more advanced conversion methods, known as *hydrotreatment*, jet fuels may be produced from TAGs (Serrano-Ruiz et al. 2012). However, with the exception of oil palm, the volume produced per hectare and the net energy return are small compared to corn and especially sugarcane ethanol.

Furthermore, all the lipid production in the world would meet only about 20 percent of diesel use, so biodiesel will not scale to a significant fraction of total demand. Therefore, we anticipate that biodiesel production will decline as technologies emerge for converting lignocellulose to liquid fuels that are similar to diesel and jet (Youngs et al. 2015).

Recent breakthroughs in engineering the accumulation of TAG in vegetative tissues of plants (Winichayakul et al. 2013) may open the way to convert highly productive plants such as sugarcane and sweet sorghum into more productive oil crops. Although biodiesel production from algae has received much attention, detailed system evaluations continue to yield costs in excess of $3 per liter even when assuming high pond productivities, which have yet to be substantiated on an annual basis (Long et al. 2015a; Quinn and Davis 2015; Sun et al. 2011).

Land Competition

A recent analysis of 80 studies suggests that bioenergy production could reach 20 percent of all energy use, which is equivalent to the total energy used today in transportation (Slade et al. 2014). While estimates vary greatly, depending on assumptions, the key point is that biofuels will compete with other land uses. This has generated concern that biofuels will displace food production or seminatural ecosystems.

Most proponents of cellulosic biofuels generally place a high value on food security and ecosystem conservation and share concerns about competing land use, but consider climate change a larger threat to food production and the environment than biofuels because it is not possible to control which hectares are affected by climate change whereas humans *can* decide which hectares are allocated to biofuels. If biofuels reduce GHG emissions, it will be worthwhile to allocate some land to achieve that benefit, especially if combined with carbon capture and storage (IPCC 2014).

Moreover, a significant amount of land that is not used for food production, or is used very inefficiently, could be used for perennial biofuel feedstocks. For land that has fallen out of row crop production, the planting of productive perennials, such as *Miscanthus* or switchgrass, would add positive ecosystem services; for example, their productive root systems would protect against erosion and add more soil carbon than if the land were simply left, grazed, or planted to trees (Dohleman et al. 2012).

Studies of historical land use have found that more than 500 million hectares of previously farmed land have been abandoned (Cai et al. 2010; Campbell et al. 2008). Such abandoned land is usually of poor quality, making it attractive for biofuel feedstock production. Lignocellulosic fuels can be made from essentially any plant species, including those adapted to growth on marginal lands, without the need for large inputs of fertilizer, energy, water, or agrichemicals (Davis et al. 2014a). In addition, approximately one quarter of the terrestrial surface is used for grazing. Is that really the best use of so much land?

Food versus Fuel

In many regions of the world, food production is not limited by a lack of arable land but rather by the exclusion—through price support systems, lack of demand, and most notably the European Economic Community (EEC) 1988 set-aside scheme (Regulation (EEC) 1272/88)—of globally significant amounts of land that could be used for food production. Indeed, total crop acreage in the United States has been on a long-term downward trend—from 102 Mha in 1990 to 96 Mha in 2015—partly because of payments to farmers to enroll land for nonproduction under the USDA Conservation Reserve Program and partly because of abandonment of nonprofitable land use (Loveland and Acevedo 2014; USDA 2013).

In the food versus fuel debate, real concerns are less about the availability of food and more about the price of food and feed. Economic theory predicts that any increase in demand increases price. Economic analyses of the effects of biofuel on food prices indicate that biofuels made from food and feed crops do increase the price of food, but estimates of the magnitude of the effect vary widely (Condon et al. 2015).

Averaged across 29 economic models, production of an additional 4 billion liters of corn ethanol in the United States would increase the price of corn by about 2.5 percent. Because the price of grains is a very small portion of retail food prices in developed countries, such small increases have an insignificant effect on consumers. But in regions with large numbers of urban people who live on a few dollars a day and depend on raw grains, such increases may have significant effects. Thus an argument can be made that biofuels harm the most vulnerable people in the world (Wright 2011). On the other hand, rural small farmers who are among the poorest people in developing countries benefit from higher prices, which provide economic incentives for them to invest in increasing production (Achterbosch et al. 2013; Tyner 2013; World Bank 2008).

Lignocellulosic fuels can be made from essentially any plant species without large inputs of fertilizer, energy, water, or agrichemicals.

Farmers should not bear the cost of feeding the world's poor but should be free to sell to the highest bidder, as with most other producers of goods. It is the responsibility of the larger society to ensure food security for the poor. And it is surely the role of governments to purchase food and provide it to the poor, or provide the infrastructure to improve production through research and extension support to ensure supply, and not impede market mechanisms to try to drive down the prices that farmers can get.

In regions where social equity does not exist or where wealthy elites control a disproportionate share of the land, acreage could, in principle, be directed to the production of biofuel for trade on world markets at the expense of food production. A partial solution to such a scenario is to establish enforceable standards for sustainability and social equity that assure prospective biofuel-importing countries that biofuel production was carried out under acceptable conditions (Achterbosch et al. 2013). Several organizations, such as the Roundtable on Sustainable Biomaterials, have emerged to manage such certification.

Finally, it is important to recognize that biofuels can increase food security by creating a buffer of plant growth that can be repurposed from biofuel to food uses during a crop failure (Wright 2011). Indeed, the biofuel mandates associated with the US Renewable Fuel Standard legislation have such a provision.

In summary, biogas or biodiesel can be simply produced and can increase quality of life in rural locations in poorer countries where access to markets is impaired by distance, poor roads, and lack of transport infrastructure. In such locations food may be produced inexpensively, while petroleum products trade at severalfold the prices in urban areas and electricity supply may be nonexistent. In these areas local biofuel production can provide energy for pumping water, lighting, communications, and refrigeration (Achterbosch et al. 2013; Souza et al. 2015).

Looking Forward

Several large trends loom over the future: Global population will expand, especially in cities, and the climate will continue to change (Long et al. 2015b). Changing diets associated with urbanization will increase demand for food and feed. Climate change will affect agricultural productivity and will almost certainly increase pressure on many ecosystems and the services that they provide (IPCC 2014).

Against this backdrop, it is fair to ask whether biofuels can have a positive effect rather than making matters worse by exacerbating pressure on land use.

One answer is that in a perfect market economy advanced biofuels and sugarcane ethanol may be important sources of liquid fuels as they become less expensive than GHG-emitting liquid fuels that are subject to carbon taxes that fairly account for environmental damages. And, as truly renewable fuels, they offer energy security far into the future. By contrast, corn-based biofuels may gradually disappear because of the relatively low level of net GHG savings and the higher demand for grain associated with population growth (Long et al. 2015b).

As noted earlier, it is impossible to know how much biofuel will be produced in the future because the many assumptions underlying the models cannot be agreed upon, but the International Energy Agency estimates that bioenergy will provide about 27 percent of total human energy use by 2050 (IEA 2011). It is conceivable that bioenergy use, which today is primarily combustion of solids, could evolve to greater use of liquid or gaseous biofuels. Sustained public and private support for continued technical improvements, together with effective and enabling policies, are required to fully realize the potential of bioenergy.

The probable impact of climate change on the availability of land for food, feed, and biofuel production is speculative because of the dependency of such predictions on (1) climate models that yield very varied regional predictions of future temperatures and soil moisture, and (2) crop models that, even for a single future climate scenario, give wildly different projections (Bassu et al. 2014; Li et al. 2015).

Despite this inability to be exact about the future, it seems likely that, because of changes to rainfall patterns and episodes of high temperature and extreme weather, many regions will experience reduced productivity compared to today (IPCC 2014). On the other hand, some regions such as the Canadian prairies will experience higher numbers of frost-free days—i.e., a longer growing season—that may increase agricultural productivity. However, secondary effects, such as expanded ranges of pests and pathogens, will almost certainly be a negative factor.

In view of the implications of population growth and climate change there has recently been more interest in adapting agriculture to marginal growing conditions. Decades of research on drought, salt, and cold tolerance show that there is some scope for genetic selection or modification of agricultural species to growth under conditions that do not support currently used cultivars. It may also be possible to adapt species that naturally survive marginal conditions so that they provide useful products. In particular, species such as agave, which use a type of photosynthesis called *crassulacean acid metabolism*, have very high drought tolerance and low rates of transpiration compared to other types of plants (Davis et al. 2014b; Somerville et al. 2010). The use of these species for biofuel production and other purposes could open up billions of hectares not suitable for other types of crops.

Overall it appears likely that food-based biofuels, other than sugarcane, will gradually be displaced by advanced biofuels that will significantly contribute to the goal of reducing GHG emissions associated with transportation. Although such fuels will probably not scale to a complete solution for decarbonizing the energy used in transport, they have the potential to be a major part of the solution.

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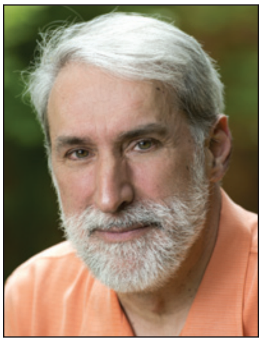
Much progress has been made in developing a scalable technology for the use of solar energy, but significant challenges remain for all current technological approaches.

The Solar Opportunity

Nathan S. Lewis



Daniel G. Nocera

Nathan S. Lewis and
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Solar energy utilization poses a vexing conundrum: at present, we cannot afford to use it, but eventually we probably cannot afford *not* to use it. The promise rests in the unmatched size of the solar resource: more energy from the sun strikes the Earth in one hour than all of the energy consumed on the planet in an entire year (DOE 2005; Lewis and Nocera 2006).

As with all energy sources, challenges for solar energy use reside in the "cost of extraction." The diffuseness of solar energy, typically providing a yearly averaged power density of about 200 W/m^2 at representative midlatitudes, requires the coverage of relatively large areas with a sunlight capture system, in turn requiring very inexpensive but high-performance materials and balance of systems to be viable. Additionally, to contribute to a large fraction of a global energy system, use of solar energy requires concomitant development of an accompanying technological approach to provide terawatt (TW)-days of reliable, robust, persistent, scalable, and cost-effective energy storage.

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Three main technologies for solar energy use involve

- solar electricity production by photovoltaics,
- solar thermal systems that produce electricity or process heat as their primary outputs, and
- nonbiological systems that mimic the process of photosynthesis through direct production of fuel from sunlight.

The status of these technologies, and the physical principles that underlie their operation, were described in a widely distributed report commissioned by the US Department of Energy, *Basic Research Needs for Solar Energy Utilization* (DOE 2005). This article provides an update on many significant subsequent developments, and identifies the challenges and associated opportunities for further research and engineering, in each of the three approaches.

Solar electricity is still a very expensive electricity generation technology when installation, capital, and operational costs are considered.

Solar Electricity

The cost of solar panels, measured in dollars per peak watt of power produced, has declined along a remarkably impressive curve, decreasing by about 20 percent for each doubling of production volume of solar panels globally (Fraunhofer ISE 2014; Jean et al. 2015). Nevertheless, solar electricity is still an extremely expensive electricity generation technology at utility scale, especially when the full costs of installation as well as capital and operational costs are considered (CCST 2011; Jean et al. 2015; NAS 2010). The potential for further major cost reductions, through both evolutionary and disruptive technology development, continues to stimulate fervent research and development (R&D) efforts in solar electricity.

Typical Materials

Devices based on crystalline silicon (Si) dominate the solar panel market (Fraunhofer ISE 2014; Jean et al. 2015). Whereas the fundamental physical design of Si-based photovoltaics has not markedly changed, significant effort has been devoted to device engineering, including novel surface passivation layers, improved contact geometries to reduce parasitic recombination processes, and the use of heterojunction overlayers. These efforts have produced steady, incremental improvements in the efficiency of Si-based photovoltaic (PV) modules. In parallel, significant cost reductions have been obtained in manufacturing costs, along with economies of scale associated with the automation of multibillion-dollar factories that yield greater gigawatt/year panel production volumes.

Gallium arsenide (GaAs) and III-V-based PV single-junction devices have been engineered through the use of sophisticated light management techniques and junction and surface passivation methods, along with epitaxial growth techniques, to produce very high-performance devices, with efficiencies greater than 29 percent (Manners 2012; NREL 2015) approaching the theoretical limit of 32 percent for a conventional single-junction device under unconcentrated sunlight. But the increased complexity of these devices results in much more expensive manufacturing costs, so such systems have not achieved significant market penetration.

Other than space-based power applications where weight as opposed to cost is at a premium, highly engineered III-V multijunction devices are currently considered viable only for terrestrial applications in conjunction with high-concentration-factor optics using solar tracking and optical concentrating systems.

Opportunities with Other Materials

Opportunities exist for obtaining improved efficiencies through spectral splitting approaches and novel designs for both 1-D and 2-D optical concentration and tracking systems and structures, and through new approaches to the growth of high-quality, high-performing III-V monolithic devices and structures.

Inorganic Thin-Film Materials

Inorganic thin-film materials use polycrystalline materials grown by a less costly, scalable manufacturing process. Cadmium telluride (CdTe)–based devices offer lab-scale efficiencies of more than 20 percent (NREL 2015) and module efficiencies of more than 12 percent (Fraunhofer ISE 2014), and are manufacturable because CdTe sublimes congruently. Devices have been obtained using engineered cadmium sulfide (CdS)/CdTe heterostructures that provide grain boundary passivation as well as control over junction recombination at the CdS/CdTe interface. Thanks to their low manufacturing cost, CdTe-based thin-film modules have captured a significant market share (~5 percent) of shipped PV modules (Fraunhofer ISE 2014).

There are long-term concerns about the availability of ample Te resources to reach TW scale and the toxicity of cadmium if it is released into the environment, but these factors are being acceptably addressed at the present installation level and with current sealing processes of the insoluble CdTe material in modules.

Copper indium gallium selenium ($CuInGaSe_2$; CIGS) and related materials systems have been demonstrated to yield efficiencies greater than 21 percent in small test cells. But the materials have been very challenging to manufacture while preserving efficiencies greater than 15 percent at module scale because of the need for precise control over the stoichiometry of this multielement material over large areas.

Thin-film materials advantageously allow the production of lightweight, potentially flexible modules that could help reduce installation costs if the highest reported conversion efficiencies can be maintained at module production scale. Alternative, earth-abundant light absorbers that could provide alternative materials options for a scalably manufacturable PV technology relative to the CdTe- and CIGS-based systems are also being explored, including detailed examinations of zinc phosphide (Zn_3P_2), group II-IV-VI materials such as zinc tin nitride ($ZnSnN_2$), and copper(I) oxide (Cu_2O).

Organic Solar Cells

Organic solar cells offer the promise of a flexible, processible, lightweight materials system that could entail very low manufacturing and installation costs. The canonical system is derived from an interpenetrating network of organic hole conductors such as polyphenylene-vinylene with functionalized buckyball-based materials acting as the light absorber and electron donor. The overall energy conversion performance has proven to be a complex function not only of the molecular composition and structure of the components, but also of their morphology, interfaces, impurities at the ppm-ppb levels and of the inorganic/organic contacts between the active elements and the metallized electrical contact layers in a fully operational device structure.

Intense research efforts have led to a steady improvement in device efficiency, with the best systems exhibiting efficiencies of more than 11 percent on small-area devices (NREL 2015). Obtaining demonstrated long-term stability at these efficiency levels is still challenging.

Dye-Sensitized Solar Cells

Dye-sensitized solar cells use an inorganic transition-metal molecular species, generally based on derivatives of ruthenium [Ru(II)] bipyridyl complexes, to inject electrons into a nanocrystalline titanium dioxide (TiO_2)–based particle network, while effecting the oxidation of an electron donor, typically iodide, in either a liquid or gel-type electrolyte (DOE 2005).

Efficiencies for small-area devices can approach 12 percent (NREL 2015), although long-term stability at these efficiency levels, especially over large areas, remains to be established. Ongoing studies seek to understand the fundamental processes that underpin efficient injection of photogenerated electrons into the mesoscopic material, the transport mechanisms of carriers through the nanocrystalline films, kinetic processes for charge-carrier recombination relative to ionic motion, and timescales for electron injection and hole capture by the electrolyte, as well as variation in these properties with the nature of the donor, electrolyte, dye, and composition and morphology of the support.

Organic solar cells offer the promise of a flexible, lightweight materials system that could entail very low manufacturing and installation costs.

The newest family of light absorber materials is based on hybrid inorganic/organic materials that consist of lead salts with ammonium cations arranged in a *perovskite* structure. The efficiencies of these systems on small test samples have skyrocketed from 3 percent to over 20 percent in a matter of 2–3 years, in a remarkable set of advances (Gunther 2015; NREL 2015). These materials offer a new paradigm for solar light absorbers because they exhibit unusually high photovoltages despite the lack of structural periodicity or long-range crystallinity and order in the absorbing phase.

These systems will likely provide new insights into fundamental semiconducting chemistry and physics, though the existing materials systems pose technological challenges: their long-term stability is questionable, and the highest reported efficiencies are fleeting in nature. In addition, the perovskite salts are soluble in water, potentially yielding toxic, soluble lead ions upon dissolution. Both the efficiency limits and the generalizability of the approach to other materials systems are ripe topics for further research.

Quantum Dots

An alternative focus for R&D involves quantum dots and related materials that could ultimately provide efficiencies in excess of the conventional theoretical Shockley-Queisser device limit. Such materials involve lead sulfide (PbS), lead selenide (PbSe), and related systems (Ning et al. 2014), as well as materials that offer the possibility of generation of multiple charge carriers from a single photon, in an inverse Auger process. Notably, both inorganic and organic systems under suitable conditions have been shown to produce multiple excitons from a single photon (Congreve et al. 2013; Schaller and Klimov 2004).

Nonbiological systems that directly produce fuel from sunlight are much less technologically developed than solar electricity or solar thermal systems.

Such approaches, along with intermediate-band systems, are in the early development stage, but offer the potential of very high efficiencies with materials that have a thin-film structure and thus low eventual manufacturing costs.

Solar Thermal Systems

Solar thermal systems involve the concentration of sunlight by optical focusing and/or optically reflective surfaces. The localized regions of heat are used to either perform chemical reactions or heat up a thermal fluid such as oil or a molten salt, with the hot fluid then used on demand to drive a turbine and produce electricity. The optical focusing and concentration systems for such installations are considered mature.

Research efforts are focused on the development of new types of thermal storage materials that can provide higher amounts of stored heat per unit volume of the thermal fluid while also being affordable at scale. Because only the direct component of sunlight can be focused, these installations require a region with a high direct normal insolation value (e.g., a desert). Generation costs have proven to be greater than \$0.15/kWh when all-in installation and operational expenses are included (CCST 2011; NAS 2010), and these costs have not declined substantially over time.

An alternative approach is to use the focused solar heat to drive chemical reactions, at theoretical second-law system conversion efficiencies that can exceed 60–70 percent. In one approach, the solar heat is used to promote the Fischer-Tropsch catalyzed production of synfuel from syngas (CO and H_2).

The cost of solar-derived heat must compete with the very inexpensive cost of heat produced from combustion of natural gas. Alternatively, solar heat can be used to drive an endothermic fuel-forming process such as water splitting; for example, molten zinc can be reacted with steam to produce H_2 and zinc oxide (ZnO). In a separate process, the ZnO is heated to release O_2 and regenerate the molten zinc (Weimer et al. 2009). Both of the process steps have been demonstrated to occur individually in the laboratory.

The engineering challenges involve obtaining a system geometry that lets focused light enter the reaction cavity and does not let much of the high-temperature heat escape, while simultaneously allowing for the input flow of the reactant and egress of the product gases in continuous or suitably large batch process modes. Additionally, the metal and metal oxide reactants must be confined in a safe and inexpensive reactor design that uses materials that are robust, inexpensive, and compatible with the reactor process operation at extremely high temperatures.

Solar Fuels: Nonbiological Production Systems

Nonbiological systems that directly produce fuel from sunlight are much less technologically developed than solar electricity or solar thermal systems, and no demonstration systems or deployed solar fuel installations presently exist. The production of fuels from sunlight offers the potential to provide a technological solution to scalable grid storage, by subsequent on-demand combustion or use of the solar fuel as a feedstock for a fuel cell, and also offers a scalable technology for the carbon-neutral production of fuels for the 40 percent of global transportation that requires a high energy density liquid fuel to function.

Chlorophyll-Based and Related Light Absorbers

One approach to solar fuel production involves the use of molecular components related to those used in natural photosynthesis. Various chlorophyll-based and related light absorbers have been assembled in conjunction with precisely connected electron donors and acceptors to achieve separation of the light-induced electron-hole pairs produced by absorption of sunlight by the chromophore of interest. These systems have advanced understanding of both electron transfer processes in molecular systems and the fundamental charge separation and transport processes in natural photosynthetic systems.

For sustained fuel production, these molecular assemblies will require coupling the photogenerated charges to multielectron/proton catalysts that can effect the bond-breaking and bond-forming processes needed to produce fuels, with the concomitant evolution of O_2 to allow for completion of a sustainable fuel production cycle. Fully functional molecular assemblies have not yet been achieved and are a target of chemical research efforts.

Challenges involve avoiding back reactions at all stages of the process, obtaining a persistent separation of the products, coupling one-electron charge separation processes to the requisite multielectron catalysts that can operate in a mutually compatible environment with each other and with the light-absorbing molecules, and achieving robustness of the entire assembly under sustained solar illumination.

Semiconductor Nanoparticles

An alternative approach uses particles of inorganic semiconductors, coupled to heterogeneous cocatalysts, to perform the light absorption, charge separation, and fuel-forming processes (DTI 2009). Upon ultraviolet illumination, materials such as strontium titanate ($SrTiO_3$), doped TiO_2, and other large band-gap metal oxides, in the presence of cocatalysts such as platinum (Pt) and ruthenium(IV) oxide (RuO_2) or iridium(IV) oxide (IrO_2), can effect the solar-driven splitting of water into H_2 and O_2.

Materials with improved response in the visible region, such as CdS or indium phosphide (InP), are generally either unstable to passivation or corrosion and/or do not provide sufficient driving force to effect one or both of the half-reactions involved with water splitting or other photochemically based fuel production. Tantalum (oxy) nitride (TaON) with RuO_x and chromium(III) oxide (Cr_2O_3) cocatalysts provide a photoresponse that extends into the visible region of the solar spectrum (Maeda et al. 2013), thus improving the solar conversion efficiency.

One approach to solar fuel production involves molecular components related to those used in natural photosynthesis.

Challenges involve identifying a suitable photocatalytic material that combines efficiency and stability, and eventually developing an approach to avoid coevolution of stoichiometric, potentially explosive, mixtures of $H_2(g)$ and $O_2(g)$.

Semiconducting Photoelectrodes

The most advanced solar fuel generation systems to date use semiconducting photoelectrodes, which combine light absorption, charge separation, and catalysis in a single material (DOE 2005).

Water-Splitting

To construct an integrated semiconducting photoelectrode, electrocatalysts must be integrated with an inherently unstable semiconductor. Metallic electrocatalysts generally block light and/or are porous, allowing the corrosive electrolyte to permeate to the underlying semiconductor (Haussener et al. 2012; Hu et al. 2014; Jin et al. 2014; Sun et al. 2015a,b). Self-healing catalysts of manganese, cobalt, and nickel (Nocera 2012) enable complete, assembled photovoltaic structures, protected by transparent conductive oxide layers, to be immersed in water and produce atmospheric-pressure stoichiometric mixtures of $H_2(g)$ and $O_2(g)$ using earth-abundant materials (Esswein et al. 2012; Pijpers et al. 2011; Reece et al. 2011).

In alkaline media, where low-resistance, intrinsically safe systems can be constructed, integrated semiconducting photoanodes have been recently developed and shown to provide operational stability and efficiency for water oxidation while operating continuously for thousands of hours under simulated sunlight (Sun et al. 2015a,b).

Research on semiconducting photoelectrodes will continue to focus on new materials for the light absorbers, separators or membranes, and electrocatalysts; new device morphologies that enable synergistic integration of the functions of the components in ways that provide cost and/or performance advantages relative to the properties of the discrete materials themselves; and new systems architectures that enable intrinsically safe operation with minimal use of scarce materials and robust product separation, to simultaneously provide robustness, efficiency, safety, and cost-effectiveness for the system as a whole. Cost-effectiveness is an especially acute challenge as the levelized cost of hydrogen from steam reforming of natural gas is $2/kg, and photovoltaics combined with grid-connected electrolyzers yield a functionally equivalent competitive H_2 production technology to direct solar-driven water splitting.

CO_2 Reduction

Solar fuel systems are also being investigated for the direct reduction of CO_2 to liquid transportation fuels, a very challenging multielectron and multiproton process.

A low overpotential catalyst for CO_2 reduction involves the use of substituted pyridiniums on certain electrode surfaces to yield, at low current densities, methanol and other alcohols, whereas metal electrodes require high overpotentials, are generally unstable at the required reducing potentials, and produce a wide array of organic products requiring expensive separation and concentration processes (Benson et al. 2008). Oxide-derived nanoparticles have been shown to reduce CO to ethanol as a major product, possibly allowing for a two-step conversion involving reduction of CO_2 to CO followed by the production of liquid fuels (Li et al. 2014).

H_2 derived from electrolysis has been used as a feedstock for an engineered bacterial system to effect the production of dilute aqueous solutions of isopropanol from sunlight (Torella et al. 2015), complementing studies that have coupled the enzyme formate dehydrogenase to a semiconductor electrode to directly produce fuel from sunlight.

A significant challenge is the instability of enzymes in vitro. Other challenges for CO_2 reduction involve the use of an expensive and/or dilute reactant (400 ppm of CO_2 in the atmosphere vs. 55 M of water for production of H_2) (APS 2011), separation of the products from the liquid electrolyte, limitations due to small mass fluxes for uptake of atmospheric CO_2 by aqueous and nonaqueous fluids, and operation under aerobic conditions without significant reduction of O_2 at the cathode or reaction of the products or intermediates of CO_2 reduction with either the evolved or ambient O_2.

Promise and Potential

Much progress has been made toward developing a scalable technology for the use of solar energy, but significant challenges remain for all current technological approaches. Most of the approaches offer the potential to provide much higher efficiencies, much lower costs, improved scalability, and new functionality relative to the embodiments of solar energy conversion systems that have been developed to date. Research, engineering, and manufacturing will need to be pursued in harmony to allow realization of the full potential of solar energy.

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Without substantially improving nuclear power, the United States is limited in its ability to enhance domestic energy and provide needed international leadership in mitigating climate change.

Requirements for the Success of Civilian Nuclear Power in the United States

Brittany L. Guyer

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Brittany L. Guyer and
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As the harmful environmental effects of burning fossil fuels are increasingly recognized around the world, the carbon-free energy generated by nuclear power plants could support increased use of nuclear power. But the progress of the civilian nuclear power enterprise in the United States is at a crossroads: Without a change in policies and public opinion, existing plants may be shut down sooner than later, and it is not clear that new ones will be constructed. Nuclear power could thus become less available as an option for climate change response—and the United States less of a factor in guiding it.

Background

Climate change requires a technological response, and nuclear power could be an important element of that response. However, current conditions in the United States may inhibit an American contribution and diminish US influence on efforts to address the problem.

If the United States is to reap the benefits of nuclear energy, it will be necessary to create the conditions under which it can flourish. Current condi-

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tions are so ill suited to its success that its failure in the marketplace is likely. Whether this will occur is fundamentally a socially determined result. Yet the question of what institutional conditions would be most effective in preventing failure has not been seriously considered, despite abundant evidence that current arrangements are not working: only a few new units have been ordered since 1974, and almost all construction projects have been plagued by costly delays.

The typically weak financial conditions of US utilities and the politically controversial status of nuclear power offer some explanation; but these factors would remain even if the use of nuclear power were to become popular. Without substantial improvement in the stability of future nuclear projects in the United States, the likelihood of their success will remain dim and the country will be sharply limited in its ability to achieve successful domestic energy solutions and to provide needed international leadership in mitigating the consequences of climate change.

Besides reducing both dependence on fossil fuels and their associated climate impacts, there are other potential gains from US progress in the development and use of nuclear power. The United States can be an international leader in nuclear operational and safety practices and in climate change policy. And it can play a key role in the development of strategies to curtail the proliferation of nuclear weapons, a major concern associated with increased nuclear energy use. Such strategies are essential, as other nations will likely develop and use nuclear energy regardless of US energy choices.

The United States is thus faced with an important question: Should it expand the use of nuclear power? If so, the American way of implementing nuclear power projects must change: specifically, a larger, but not exclusive, governmental role is required.

Early US Nuclear Development: Favorable Conditions

From its conception to its growth to industrial scale, US civilian nuclear power was marked by substantial federal involvement and subsidy. This made sense because the roots of the technology were in secret government work, introduction in 1950s of the "peaceful atom" was a federal priority, and the government believed in the potential of nuclear technology to provide great economic benefits (Kinter 1959). Federal involvement also resonated with the popular attitudes of the time (trust in the beneficence of the US government) and provided the stable environment required for the initial development of civilian nuclear power technology.

The combination of government involvement and vigorous economic growth sparked utility interest in nuclear power based on light water reactors (LWRs; Perry et al. 1977). Implementation of regional power pools and emerging environmental concerns about air quality also made nuclear power an attractive option for utilities. These features, in conjunction with the stable economic climate of the late 1960s–1970s, provided the impetus for construction of 253 nuclear power plants (although over 120 were ultimately cancelled; Gore 2009, p. 159).

Political, Economic, and Social Changes

The favorable political and economic conditions for the initiation of the large nuclear projects did not last. In 1974, driven by an unjustified concern about impending uranium shortages, the federal government withdrew its support and promotion of LWR technologies in favor of developing breeder reactor technologies.

The American way of implementing nuclear power projects must change. A larger governmental role is required.

At the same time, based upon the apparent success of the early nuclear power plants, the Atomic Energy Commission announced that the LWR technology had reached sufficient maturity and was believed to be adequately complemented by private industrial infrastructure such that it no longer required federal support. In retrospect, this proved to be a serious error, reflecting an overestimation of the strengths of private markets and an underestimation of the difficulties that have characterized most of the history of nuclear power. Too much faith was placed in the ability of private industry alone to make nuclear power more attractive than its fossil fuel alternatives. Instead, the government's withdrawal resulted in an enduring primary national reliance on fossil fuels for electricity generation.

Also in the early 1970s the social and economic stresses of the Vietnam War led to a departure from prevailing social attitudes and an unstable, hostile environment for nuclear projects. As the war became increasingly unpopular, protests against government projects became an attractive tactic for attacking the legitimacy of the government and its policies generally. Some portions of American society remain critical of things nuclear, including nuclear power.

Once the initial enthusiasm had passed, subsequent windows for nuclear power construction projects that seemed to be sensible pursuits were typically too short for utilities to complete the projects successfully.

Unfortunately, there was no significant action at the government level to bolster the project economics or provide political insulation (as is common in France, for example) so as to ensure the expansion of nuclear power. In fact, the destabilizing political and economic environments for nuclear power plant projects were not even well recognized as a problem. Thus, the political will for action to remedy the failures of nuclear power and to support its future progress did not jell, even as project cancellations became common.

Current Challenges to the Development of US Nuclear Energy

Critical Instabilities in Costs and Decision Making

The primary barrier to new nuclear power plant construction in the United States is uncertainty about the capital cost of the project (Davis 2012). Figure 1 illustrates the large variation of construction costs for nuclear power plants in the United States in the late 1960s and 1970s. In 2014 dollars, overnight construction costs for dozens of projects begun in 1967–1978 ranged from \$1,000 to more than \$9,000 per kWe for basically the same power plants (EIA 1986).

The principal contributor to the uncertain outcomes of such construction projects has been the instabilities of the decision-making environments for these projects, especially in the construction phase, which largely determines the cost of the resulting energy. These instabilities arise from the high sensitivity of the project schedule—and thus costs—to unanticipated changes, which may come from sources such as

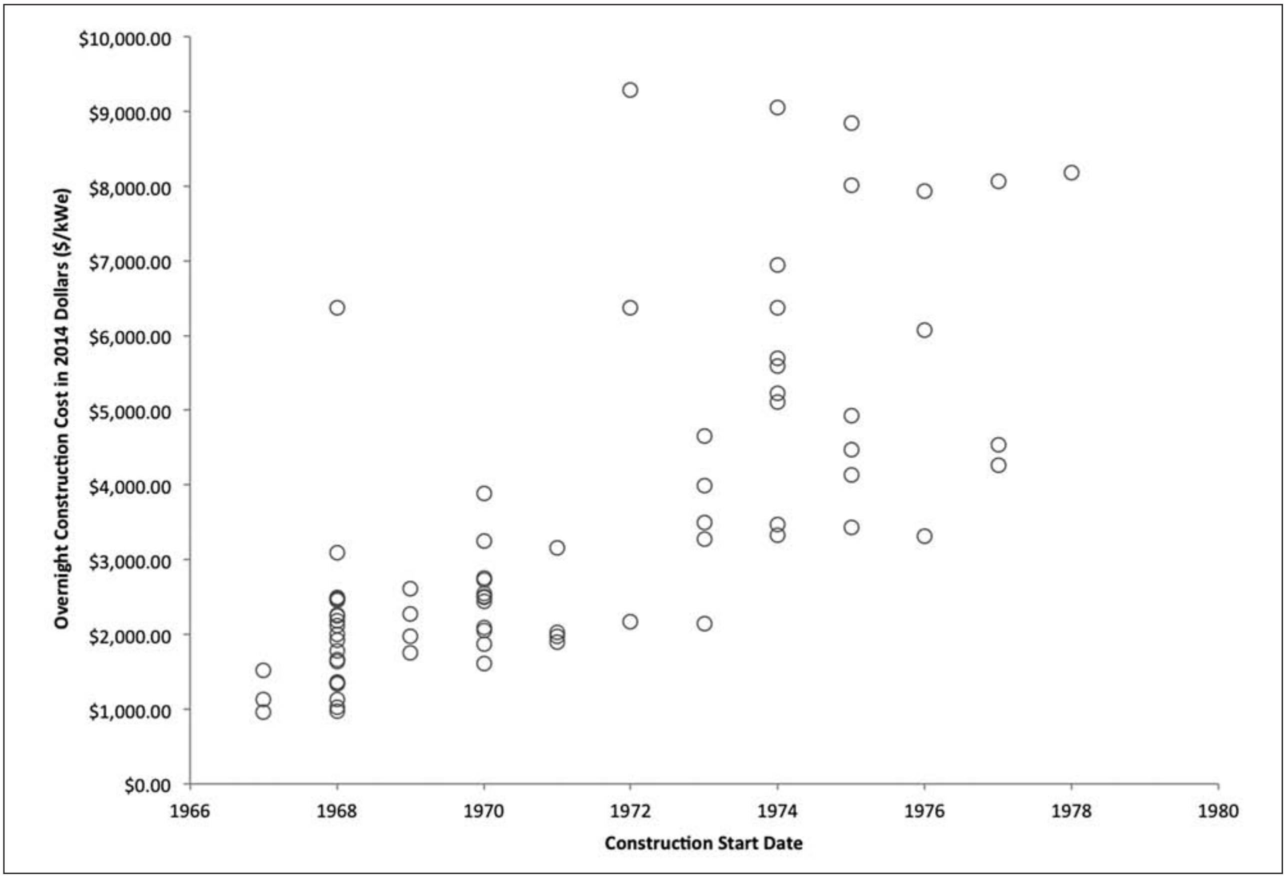

FIGURE 1 Overnight construction costs (in 2014 dollars per kilowatt electric, kWe) for a sampling of plants that began construction between 1967 and 1978. For plants not completed by 1986, estimated overnight cost is used. Based on data from EIA (1986).

the safety regulatory system (via new requirements or licensing disputes), but more often from procedural delays (especially as a result of political opposition), from design and construction errors, and from interruptions in project funding. Nuclear power plant construction projects are particularly susceptible to these instabilities because of their large financial vulnerabilities and long timescales—typically 90–130 months for completion (EIA 1986, p. 19).

Instabilities have been observed both at the level of the utility companies in charge of nuclear projects and in the federal government, which is in charge of setting policies related to them. The instabilities combine to create an unpredictable, largely socially determined overhead cost that is unique in degree to US nuclear power plant projects.

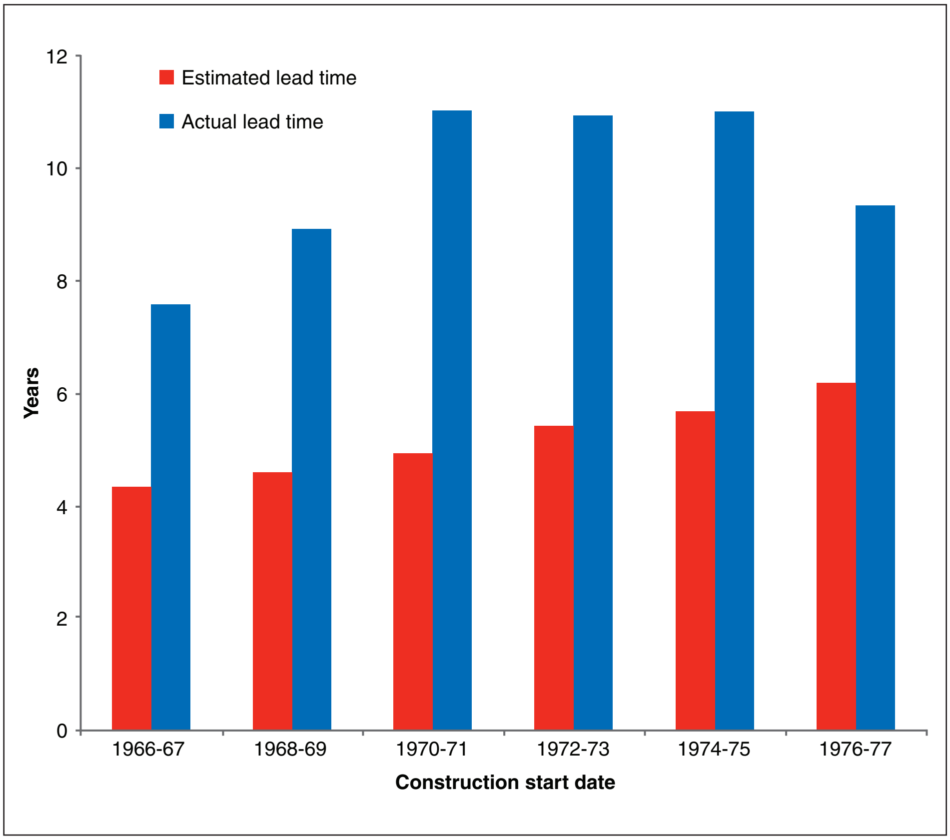

FIGURE 2 Estimated and actual lead times (in years) for plants that began construction between 1966 and 1977 and were in operation as of 1986. Adapted from EIA (1986).

Construction Delays

An important cause of the unpredicted negative outcomes for civilian nuclear power plant construction projects in the late 1970s and 1980s was unanticipated increases in lead time (Lester 1978). Figure 2 illustrates estimated and actual lead times for nuclear power plants operable by the end of 1986.

As new technical problems arose, reflecting the immaturity of the technology, they caused project schedule delays and a cascade of economic stresses. Inaccuracies in lead time estimation also meant that utilities had to purchase replacement power when they were unable to meet their electrical demands because of the lack of expected nuclear power. This not only further increased the cost of the construction project but also ultimately dampened utility interest in nuclear plants and made fossil-fueled plants more attractive as they required less construction lead time.

Public Opposition

The US Nuclear Regulatory Commission (USNRC) inadvertently became a source of instability when it allowed individuals to raise technical challenges in regulatory licensing hearings (Graham 1985). Although the challenges very rarely resulted in license modifications or safety improvements, the processes of resolving them caused costly schedule delays—and became an effective tactic of project opponents seeking to render a project terminally expensive. Growing public concern for the safety of nuclear power production, partially incited by its political opponents, thus ultimately slowed many construction projects. This tactic, expressed more at the policy level, continues, resulting in a steady accretion of costs that has effectively excluded nuclear power from the marketplace.

The Way Forward for US Nuclear Energy

Notwithstanding the many difficult circumstances that have faced the US civilian nuclear power industry, the operational success of the technology has solidified its position in the electric generation portfolio, as was clear in the US response to the recent unfortunate events at Fukushima. Even though a catastrophic accident had occurred, high-ranking government officials maintained their support for the technology, as did the majority of the general public (Newport 2012).

However, the US political system is open to small but determined groups who can use it to paralyze projects and to thwart the will of the majority. So a favorable mass opinion does not ensure project success. What is needed is governmental support (both regulatory and financial) to provide the stability needed to complete these major projects; management of public participation; technological development, in order to expand the capacity and scale of nuclear power; and policies that limit international nuclear proliferation. These four factors are described in the following sections.

The US government can create the stability required for success when a project is of great national strategic need.

Government Support

If civilian nuclear power is to be successful in the United States, it will require the establishment of a decision-making environment that greatly increases confidence in the successful outcomes of these projects. It is no coincidence that nuclear power has been most successful in France and in Japan (at least until the 2011 Fukushima event), where direct democratic participation concerning project implementation has been limited; financial security has been established, partly through governmental financial support; and the government's role in the economy is much greater than in the United States.

In France the electric utility that owns all of the 59 nuclear power plants in the country is 85 percent owned by the national government (EDF 2013). Thus, the French nuclear power program is inherently a government program. In Japan the reactors are owned by nine private utilities, but the government has encouraged and supported the growth of this sector as a strategic project in which the companies act in effect as national agents (EIA 2014). Even with this structure, the Fukushima incident showed that a wealthy investor–owned company—much larger than those of the United States—can be overwhelmed by a catastrophic nuclear accident. The owner of the affected plants was effectively destroyed financially, and the government became their de facto owner by default.

We argue that the future successful use of nuclear power in the United States will require much greater active governmental involvement and support than has been seen since 1974, when the US nuclear power enterprise was effectively turned over to the private sector. Since then the combination of the high potential costs of nuclear projects, their socially volatile nature in the American context, and the financial weakness of the private firms involved has shown that nuclear power in the United States is unsuited to the private sector.

Although traditionally the US government has not been heavily involved in stimulating specific industries, it has created the stability required for success when a project is deemed to be of great national strategic need. The prospect of climate change could easily play this role for nuclear power in the future.

In the late 1960s–1970s, for an illustration of how swift and resolute the response of the political system can be when urgently challenged, the US government adopted stabilizing measures in the wake of a political battle in both the judicial system and Congress over the legalities of the construction of the Trans-Alaska oil pipeline. When the 1973 oil embargo occurred, Congress took quick action to eliminate all barriers (including satisfaction of National Environmental Policy Act requirements) to construction of the project and created financial incentives to address what was thought to be an imminent need for increased domestic oil resources. The swift government action created the stability required for the completion of the pipeline.

If the political will existed to support a more active role for the US government in promoting nuclear power, a government-owned company might be established to accomplish this objective. Although it is not a commonly used strategy, there is precedent for such an approach as exemplified by the creation in 1933 of the Tennessee Valley Authority (which currently operates six nuclear power plants, among others) and in 1937 the Bonneville Power Authority. Because the federal government would assume ultimate responsibility in the event of a nuclear catastrophe (as the government did in Japan and as would be the case in the United States under the terms of the Price-Anderson Act[1]), a government-owned company would provide the means for a nuclear power plant operator to take responsibility for significant liabilities after a serious nuclear accident—and it could provide a reflection of the social will concerning nuclear energy, as the creation of such an entity could be realized only through congressional support.

Better-Managed Public Participation

Limiting the access of politically motivated participants to the regulatory review process can allow for more stability without impairing safety, and in recent years public access to regulation has in fact been steadily reduced to increase the efficacy and predictability of the process. Completely eliminating public access would go against the uniquely American approach to nuclear safety regulation, but carefully limiting it can reduce opportunities for political guerrilla warfare in the regulatory process.

The case for the reduction of public involvement is strengthened when one realizes that citizen participation in licensing has done little for safety but has occurred at enormous cost (as explained above). Most other nations, such as France, Sweden, and the United Kingdom, have demonstrated that effective nuclear safety regulation does not require direct public participation. In fact, no other country regulates in the American way. It may thus be reasonable to suppose that the US nuclear safety regulator could successfully carry out its expert responsibilities with reduced or minimal public participation.

Technological Development

If nuclear energy were to become an important part of a climate change mitigation response program, it would be necessary to develop the technology in terms of both the needed scale and products provided. To ensure a carbon-free world, substitutes will be needed for electricity, heat, and fossil fuel. Of the current technologies capable of supporting such substitutions, only hydroelectricity and nuclear energy are available at the scale required, but they produce only electricity. If they are to be effective fossil fuel replacements, they need to be capable of producing more than electricity and on a much greater scale. This eventuality implies the creation of a very different energy economy, relying on a mix of renewable, geothermal, and nuclear technologies.

In pursuing expansion of nuclear power, the United States could be a leader in the development of a stronger international nuclear control regime.

Protection from Nuclear Proliferation

The challenge of ensuring control of weapons proliferation needs to be resolved satisfactorily. By actively pursuing an expansion of nuclear power, the United States could take a leading role in the development of a stronger international nuclear control regime, which is recognized as a necessary means to limit proliferation risk but has received too little support from the world's leaders.

For commercial nuclear power to be both successful and safe worldwide in the long term, the United States and other leading nations must support more robust international controls against nuclear proliferation. Weak safeguards may prevent nations from achieving the climate change benefits that nuclear power can provide and are therefore just as important as a favorable political and economic environment for commercial nuclear power.

Conclusion

If concerns about climate change and energy independence grow significantly in the future, it is plausible that nuclear power will attain in the United States the level of public support that it has experienced in other countries, such as France, Japan (before Fukushima), and more recently China. But a supportive public attitude alone will not be enough to support the increased use of nuclear power in the United States.

[1] From the website of the Nuclear Energy Institute (www.nei.org): "Congress passed the Price-Anderson legislation in 1957 as an amendment to the Atomic Energy Act to ensure that substantial funds will be available to compensate the public in the event of a nuclear accident. Through this program, the nuclear energy industry maintains $13.6 billion in liability coverage."

The use of nuclear power to respond to climate change will require substantial institutional and organizational changes, such as market interventions, and governmental activism, both organizationally and financially. Market stability must be created for the technology in order for it to prosper in the US economy. If society accepts a greater role for the government in the expansion of nuclear power generation, it may also support the government in creating the environment necessary for success in this national energy strategy. How this situation evolves will be very important in determining the ability of the United States to provide world leadership concerning both expected climate change and nuclear proliferation.

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Op-ed

Getting Off Fossil Fuels

Michael W. Golay is a professor in the Department of Nuclear Science and Engineering at the Massachusetts Institute of Technology.

Climate change is coming surely and swiftly. Studies by atmospheric scientists indicate that substantial global warming (>2°C) is likely within about 60 years if current economic and energy consumption trends persist.[1] Without a transition to a low-carbon energy economy within that timeframe, greenhouse gas emissions will continue and contribute to even greater warming.

Emissions of CO_2 into the atmosphere not only have immediate and long-term effects but also are almost irreversible. Their immediate effect is to warm the air and soil; further warming then occurs as heat is transferred from the atmosphere to the oceans and deeper into the soil, increasing glacial melting and seawater expansion and, on land, vegetative growth and organic material decay.

Now is the time to determine what to do about this problem—specifically, how to move the global energy economy off fossil fuels. Private markets alone cannot achieve the technological capabilities needed to prevent further warming, but they *can* be stimulated by the public sector in the most capable (and most energy-consuming) countries. What's needed are a clear international vision of goals. This note offers such a vision.

The future energy economy is likely to rely on a mix of renewables, nuclear energy, and synthetic fuels that can be used as substitutes for current fossil fuels (perhaps using recycled carbon, or noncarbon fuels, such as those based on ammonia) to provide abundant heat and efficient use of input resources (e.g., fuels, land, water, and labor). Synthetic fuels may become a major means of energy storage, and technologies such as carbon capture and sequestration and geothermal energy may also be important.

Performance requirements will include the ability both to produce energy on a scale greater than that of current consumption (e.g., >10,000 GW) and to provide electricity and fossil fuel substitutes (or their constituents such as heat, water, and hydrogen).

Siting decisions for alternative sources of energy will depend on the particular strengths of a location (e.g., for renewable technologies, access to strong wind or abundant sunlight). The resulting nonuniform distribution of sites would require operational scheduling and transportation of their products; dispatchable operations would be favored where possible.

With nuclear technologies, requirements for both very high safety and control of the risks of nuclear weapon proliferation would likely limit their use to industrialized countries, which are generally capable of strong controls in both areas. Nuclear products, such as synthetic fuels, would be provided to other countries but power reactors would not. Economies of scale and assurance of control might favor international, perhaps continental, arrangements for both nuclear fuel and waste disposal. If these cannot be achieved nuclear power may be nonviable, despite the likely severe need.

A market that permits economic competition among technologies offers the best promise of good results (in part by excluding unacceptable ones). But in the current energy economy, fossil fuels are sure to win in the economic competition among energy sources because they are superior to the nonemitting alternatives in terms of cost and convenience. Strong, large-scale government involvement in market policies and

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Readers wishing to comment on this piece are invited to contact the author (golay@mit.edu) and/or *Bridge* editor in chief Ron Latanision (rlatanision@exponent.com).

[1] Solomon S, Plattner G-K, Knutti R, Friedlingstein P. 2009. Irreversible climate change due to carbon dioxide emissions. Proceedings of the National Academy of Sciences 106:1704–1709.

technology development is therefore essential both to change the rules of markets and to support the rapid development of needed technologies, which cannot be attained quickly enough from the private sector alone.

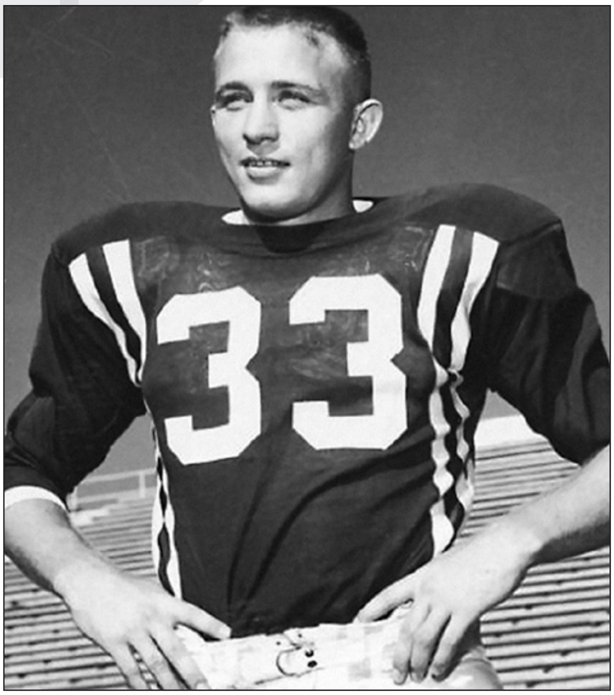
Government leadership will include consensus for urgent action, international cooperation, and policies such as heavy carbon taxes. Also needed are near-term harmonization of renewable technologies in the global energy mix, the policies and technologies to sustain them over the long term, and government incentives and direct support of technological development. These measures will require an international effort in which the largest economies (China and the G-7 countries, especially the United States) will lead because they have the greatest resources.

Bearing in mind that future versions of both renewable and nuclear technologies may be substantially different from those either in use or being pursued, strategies are needed for government programs to (1) formulate market policies, (2) fund progress on difficult long-term technological problems that are not adequately addressed in the private sector, (3) stimulate private sector actors to improve the energy economy, and (4) focus on long-term technological development.

The challenges are urgent but remain largely unrecognized as near-term problems at high governmental decision-making levels. The measures outlined here offer steps toward mitigating the impacts of climate change by redirecting the current energy economy away from fossil fuels in favor of sustainable alternatives.

An Interview with . . .

Charley Johnson



Charley Johnson is a retired professor of chemical engineering from New Mexico State University and a former Denver Broncos quarterback.

Ron Latanision (RML): Good morning, Charley. We're so glad to talk with you. How are you? We understand you had some health issues.

Charley Johnson (CJ): I'm fine. I've been accepted to a stem cell treatment for my hip and my knees.

Cameron Fletcher (CHF): Fascinating—stem cell treatments for joints.

RML: That must be pioneering.

CJ: Pretty close. They started doing some experimental treatments two years ago. Several of my Bronco teammates were involved in it; they were telling me about how super it was so I looked into it and applied and I get to do it. I'm scheduled for June 10th.

RML: That will make an interesting follow-up; we ought to keep in touch with you as this progresses. Actually, in the *Bridge* we focus on subjects like the introduction of engineering in medical research. What you are talking about is a great example—the fact that engineers' impact on medical research is really changing the face of medicine.

CJ: And with all the advances in physics and high tech, they can do so much more so much faster.

RML: Absolutely. We also include issues on fracking and nuclear waste management, things that are typical of engineering. A few months ago it occurred to us that engineers also impact the culture of the country in lots of ways far beyond building and managing engineering systems. So we introduced an interview column in which we talk with people who have both an engineering background and some major impact in terms of the culture of the country. I was delighted to learn that you're a chemical engineer and available and willing to talk with us.

CHF: Yes, thank you very much. This is exciting.

CJ: It is for me too.

RML: I've got to ask, Charley, how you pulled all this off? I have been reading up on your background. You got a BS in chemical engineering in 1961, you played professional football for the next 15 years, and while you were playing you were also on active duty in the Army. You played quarterback on Sundays and found time during all of this to earn a doctorate in chemical engineering from the Washington University in St. Louis. How did you manage this?

CJ: Well, I started out in a military junior college in Kerrville, Texas. When I came here to New Mexico State University, it was also a military school, like Texas A&M. I was going to be a career Army officer. But my football career took off and the Army allowed me a delay for graduate school before I had to go on active duty. So not only did I graduate but I also got commissioned and, since the Cardinals had drafted and signed me, I applied to Washington University in St. Louis for grad school. I got in and the way the workouts and the classes were scheduled I was able to go to class early in the morning and late in the evening, which left me all day to go to football practice.

I played, I got my master's in two years, and started on my doctoral program. Then I had some problems with injuries and started flunking my annual Army physical, so I did not do my required 12 hours as a full-time graduate student. Boy, they snapped me in right away when it was at the height of Vietnam. Fortunately I did not have to go but I had to go on active duty.

CHF: It is very fortunate that you did not have to go. Was that because of your injuries?

CJ: Right. I never passed a physical—I was too beat up for combat.

CHF: But not too beat up to play professional football!

While I was playing with the Cardinals, I spent two years at NASA Langley doing research, which was accepted for my doctorate.

CJ: No. In football I could fall down and hurt myself, but in combat that would have gotten a lot of guys killed, that was the reasoning. So they assigned me to NASA, the Langley Research Center, in Newport News, Virginia. I spent two years there doing research, which was accepted for my doctoral research.

RML: Much of this happened while you were playing with the Cardinals, is that right?

CJ: Yes, all of it. When I got traded in 1970 to Houston, I was following my St. Louis coach, who had been fired from the Cardinals and went to the Houston Oilers, so I asked to be traded down there. I finished writing my dissertation in Houston.

RML: That was about as convoluted and difficult an approach to getting a doctorate as I have ever heard!

CJ: I was very fortunate. I lost my first advisor on my first research program at Washington University, but the guy that came in and took his place was fantastic. I really did not lose a lot of ground by changing advisors. Normally you just start over, but I did not have to because I had the NASA research.

RML: What was your research focused on?

CJ: At NASA they had discovered a high-temperature polymer that basically would not melt, but they did not know how to process it to make useful things out of it. That was my project. I figured out a way to do it.

CHF: What were some of the useful things made out of it?

CJ: A lot of the parts that went into space capsules and rockets.

RML: Actually, I spent part of my career in academia and had a student from NASA Langley whose name was Ron Outlaw. Does that name ring a bell?

CJ: Yes, I don't know why but it does.

RML: He was a doctoral student of mine at MIT many years ago. I don't know where he is now but I know he was at NASA Langley.

CJ: I was there '67, '68, '69.

RML: He would have been there then.

CJ: I was in the chemistry and physics branch of applied materials.

RML: He was focused on materials. My guess is that somewhere along the line you may have crossed paths.

CJ: We could have been in adjoining labs and never saw each other.

RML: After your football career ended you began teaching at New Mexico State.

CJ: I spent basically 25 years in Houston working in the gas business. I designed, built, and operated compressor stations for pipeline companies. I got into that because one of my neighbors in Houston had a company that did that; I worked for him for three or four years. Then I went with a guy out of Oklahoma, helped him start a company. Then I started my own. I caught a really, really good year in 1990. But by '98, it was back on the bottom again and I got an inquiry from New Mexico State about applying—one of my old friends was on the search committee and asked me to apply. I said, "Come on, I have applied out there for a head coaching job, I applied to be on the faculty, I never even got a response." He said, "Well, I can't promise you a job this time either, but I know you will get an interview." So I applied and went through the interview process and they offered me the job and I just had to take it.

RML: What year was that?

CJ: That was 2000. I applied in '99 and got the job as head of the Department of Chemical Engineering in 2000. I was head of the department for 4½ years, then I got into just teaching and had a ball for 25 semesters.

RML: This just adds emphasis to the comment that I made at the beginning. You have had a truly remarkable career.

CJ: Very fortunate, even though I need stem cell treatment now.

RML: Well, as we age, whether we have been on the gridiron or not, we tend to need all sorts of medical attention—although you probably have a few bumps and bruises that are a little more unusual.

CJ: I have only had surgery 17 times. I may have brain problems but I don't remember.
(Laughter)

CHF: You have done teaching and you have been in the gas industry and the space industry and professional football. Do you have any personal favorites in your varied career?

CJ: Not really. It was all fun.

RML: I would imagine there must be some really great and memorable occasions from football. If you were to identify what were among the most memorable of your experiences given this broad range from sports to academia to industry, what would turn out to be the most memorable of those experiences?

CJ: Probably having my mom there when I graduated with a doctorate. The hood was pretty fantastic.

RML: They are pretty colorful, aren't they?

CJ: Yes, Washington U really was and I've worn it many times since.

RML: When you were teaching, did the grad students or undergraduates ask you for football stories?

CJ: Not really. Seemed like I indoctrinated freshmen every year and they did not know who I was. The graduate students knew and would ask occasional questions but I kept them pretty busy in my classes. We did not have any time to talk football.

RML: When you were department head, were you also teaching?

CJ: No, but I had the freshmen for a couple of classes a couple of times just to try to get them ready for how hard the program is.

CHF: Was there any cross-pollination in your approaches or thinking about your teaching, for example based on your experiences on the field in football or at NASA?

CJ: I liked the discipline part. It is hard to get across to freshmen in college engineering—even as sharp as they are to be able to get in, they have no idea how hard it is going to be. For me there was some crossover from the difficulty with Army courses, Army learning, in addition to the NASA research learning. I enjoyed that.

CHF: How did you specifically draw on those experiences to help you reach these young students?

CJ: I got after them on their grammar first. So many of them had the "you know" habit and the "where you at" habit. I just nailed them. Any time their phone went off they had to get up and get out of the room. All those things that interrupt the learning process—I could not stand it. It drives me crazy for professional broadcasters to use those terms, and for some high-powered politicians to say *you know, you know, you know*. I keep saying *no I don't, no I don't, no I don't.*

RML: I really like the concept that you just expressed about discipline with students. I think the one thing that young people often don't appreciate is how much effort it takes to be good at whatever you do. Even if you are born with some native talent in an area, you still have to practice, you have to work at it.

CJ: The smartest guys or women that I had still had to learn the discipline part. As smart and sharp as they were, if they were not disciplined to be ready for an exam or to finish an assignment, they got in trouble. They embarrassed themselves, they embarrassed their family. I tried to embarrass the hell out of them. They could do as well as they wanted to. Sometimes they just got caught up in other stuff, like we all do.

RML: Tell us a little bit about the compressor corporate involvement. You were involved with compressors for the oil and gas industry?

CJ: Natural gas compressors, yes.

RML: How did you launch into that?

CJ: When I got traded to Houston, we built a house there and the guy down the street was just starting up a compressor company. I got to know him and learned about what they were and how they worked and all that good stuff. Then I travelled around with him getting this company started and established. I was basically a token jock salesman. But we got it going pretty good and got up to about $5 million, I guess, in three or four years. I really enjoyed it, I enjoyed the people. I worked with top-notch engineers in the different companies.

It was really big for us to go into Cleveland in 1964 while they were defending champions, and we wiped them out.

When I finally started my own company it was marvelous. It was tough to start with. I was down to my last credit card when I went to California to sell a project to California Energy. I got the contract—it was a $4 million contract, and I got a down payment of several hundred thousand. I flew back home to Houston with a big check in my pocket.

RML: Must have been a really good feeling!

CJ: Oh, yes.

CHF: Did you ever find that your renown on the football field helped open doors in your business?

CJ: In just about every case, yes. Most engineers are pretty much aware of athletics.

CHF: Were people surprised or maybe even skeptical that a big name jock like you would be so capable in engineering?

CJ: Those that kind of knew what it took to do both things, yes. It was impressive to the younger guys for sure. The old hats, they had a tendency to kind of disregard until they had to call me CJ—attitudes changed all of a sudden.

RML: Did your chemical engineering experience ever play any role in a football game or in your football career?

CJ: No, just the discipline part.

RML: Let me ask you about "Deflategate"—that involves some chemical engineering.

CJ: Boy, they messed that up badly, didn't they? Oh, gosh. In practical terms, it was a matter of feel. It did not have anything to do with the pressure in the ball—that could vary from 10 to 13 psi—but that really did not have that much to do with it. The passer can't tell what the pressure is, he can just tell how it feels.

RML: There has been so much controversy and I am especially sensitive to it given that I live in Boston. Tom Brady said he never measured, and Bill Belichick—neither of them claimed to have any idea what the pressure in the balls was or should be. They just, as you said, made their judgments based on how the ball felt. There has been some interesting follow-up in the press. Some of the local academics, given the Boston academic community, generated theories based on the ideal gas law and other things that make a certain amount of sense.

CJ: It is going to change significantly, but maybe not feel-wise, when you take a ball from a 75° locker room out to a 10° field. They can figure out how much it is going to change, but nobody ever did because it was a matter of feel.

RML: There have been some estimates in some of the newspapers in which they project something like maybe a pressure change on the order of a psi. When you are talking about a ball inflated close to the minimum, if you go out of the locker room onto the field, just as you say, as the temperature decreases the ball pressure is going to decrease. So it has become an interesting question of chemical engineering and chemistry and physics. What do you think the NFL is going to do? Do you have any thoughts on that?

CJ: They will have an official check them and make sure they are all within the boundaries.

RML: While we are on the subject of the Patriots, I thought I would look into the record book and find out what kind of history you had against them.

CJ: Almost zero.

RML: During your Cardinal years they were in the AFC and I guess there wasn't any play between leagues except in the championship games and the Super Bowl. I found that you played the Patriots one time. It was in December of 1972, and you beat the crap out of them, frankly—three touchdowns, about 400 yards, something like that. You had a good game. What was your most memorable football game?

CJ: Probably throwing six touchdown passes at Cleveland in '65 when they were the defending champions. Second game of the year, we just shocked them.

RML: Which year was that? Were you a Bronco?

CJ: '65. No, I was at St. Louis.

RML: That would be memorable.

CJ: In '64 they won the Eastern Division and shut out Johnny Unitas and the Colts in the Western Division for the championship. That was the first year the league started having kind of a play-off system. So the Cardinals played Green Bay in a "runner-up game," they called it, and we beat Green Bay. We were right there with Cleveland. I think they beat us out by half a game that year. It was really big for us to go into Cleveland while they were defending champions, and we wiped them out.

RML: I know that a lot of people have given you a great deal of credit for turning around the Broncos when you joined them in 1972. My reading suggested that that is an accurate statement. Before you joined them they did not have many winning seasons. That turned around pretty quickly.

CJ: In '73 and '74 we had their first two winning seasons ever. So yes, they like me for that.

RML: Do you have contact with the Broncos today?

CJ: As a matter of fact, I am going up for a Bronco reunion June 7 and 8. The stem cell institute is in Fort Collins, 60 miles north of Denver, so that is going to work out beautifully.

RML: Good timing all the way around. Today is also a good day in terms of the draft. Do you have any thoughts on the NFL draft today?

CJ: I kind of enjoy the controversies involved. Nobody knows who is going to turn out to be the best number one choice or the best tenth choice. It is really a gamble. The Cardinals had number one draft choice several times when I was with them and I don't remember one of them really working out great.

RML: In New England there has always been a lot of fascination with the draft. If you look at Tom Brady, for example, he was not a high draft choice, yet he has had a truly remarkable NFL career.

CJ: One of a kind, nearly.

RML: I just don't know how people gauge the talent they are looking at. I am sure having something like a Heisman Trophy in your possession is a pretty good credential.

CJ: But not always.

RML: Not always, no. I was trying to think of a Heisman Trophy winner who has gone on to have a remarkable NFL career. I can't think of very many.

CJ: John David Crow comes to mind because he was a teammate at St. Louis. But you are right.

RML: It often turns out to be a different world when people leave college and go on to the NFL.

CJ: As big a change as going from high school to Division 1 college football.

RML: Now that you're fully retired, what keeps you busy? What kinds of things are on your radar screen?

> *I love doing woodwork, I make fishing lures, and I started building golf clubs. I am after the Holy Grail of the longer drive.*

CJ: My wife has a to-do list that is about as long as my arm. I kind of do handy stuff. My knees have prohibited my climbing ladders anymore, thank goodness. I still have a hobby: I love doing woodwork, I've got several different kinds of saws. I started building golf clubs and I really enjoy that, and I make fishing lures. I've got plenty of things to do.

CHF: You make golf clubs?

CJ: I buy the parts. I buy the grip and the shaft and the head and I put them together. That is why I have about 250 golf clubs here. I am experimental.

RML: What is the nature of the experiment? Are you looking at different mass? What kind of variables are you looking at?

CJ: Overall weight, head weight, swing weight, how limber the shaft is, and how they will help my swing. I am after the Holy Grail of the longer drive. And the Aggie head football coach wants me to help out with the quarterback. He was a quarterback at Kentucky and he has got a really good kid coming up who is going to be a junior but has never really learned football—the idea of down in yards, position on the field, score, timing to go, all those things—so he is kind of lost out there as to what to do when he goes back and nobody is open. He led the nation in throwing interceptions last year but he is really, really good. The coach wants me to help him in learning the game itself. That is going to be fun.

Opportunities are going to come along for all of us. Being able to recognize them and to perform is the most important thing.

RML: You have done some coaching over your career, is that right?

CJ: I coached the Bronco quarterbacks the year after I retired from Denver, but that is about it. I helped coach some pee-wee teams in Houston, and some pee-wee basketball. Of course, I've got to help with my daughter's softball team. And my son has been coaching for 25 years. He is assistant to the head football coach at a 6A school down in the Valley of Texas, close to Brownsville. He loves it. His wife is from Weslaco, and they have three girls. The oldest is here at New Mexico State with us now and doing very, very well.

RML: That is great. I am still intrigued by your comments about discipline and the need to somehow instill in young people the concept of understanding how important that is. I am afraid that kids are getting lost. I am watching what is happening in Baltimore; but it is not just kids in areas of conflict. There are kids all over the country that are so distracted by social media and games that occupy a lot of their time. They seem to lose track of the fact that in order to be good students, successful students, they have got to work at it. Discipline is really lost. I am wondering if you speak to students. Do you make any engagements to talk to kids at college or high school or anywhere else?

CJ: I have not in the last couple of years. Of course when I was teaching I did quite a bit of it, at high schools and elementary schools. But I think a lot of it is the excitement that we all felt when the computer was so fantastic and there were so many games to play on it and a lot of them were pretty good and not only entertaining but educating. I remember our being very positive about the impact the computer was going to make on young people. Sure enough it got waylaid by technology, where it is just fun and no learning anymore. I guess it is fun; I don't do games or social media or any of that junk.

RML: I guess we are of the same mind on that. In many ways it is sort of an unintended consequence of what appears to be—and is in some respects—a really great advance. A lot of students that I have worked with over the years have become involved with electronic technologies through modeling and simulations of chemical and biological phenomena. That can be really powerful.

CJ: Without a doubt. 3-D printing is going to be awesome.

RML: Absolutely. But I do worry. I have five grandchildren and they are all adept with keyboards. They are young so most of the time they spend on keyboards is games that are sort of mindless, repetitive exercises; I don't think there is much learning in them. There are certainly games that do have educational content but a lot of what I see my grandchildren playing with is not particularly educational. That worries me. I have this feeling that, for those of us who have had some experiences that might get kids' attention, it might be useful if we became involved in trying to instill in these young people the concept that they really have got to be disciplined. They have got to work at learning and work at making themselves useful citizens. That is something that we have kind of lost.

CJ: Absolutely. I spoke earlier this spring at the football banquet of a high school team. The room was packed and full of parents. I got into just that: Spend your time doing things that are going to help you in school. Always be ready to do your best when you have a challenge, whether it is a test or a ballgame or whatever. The parents were dozing off. I was so surprised. They were paying no attention. The kids were reacting but not the parents. I was very disappointed. I thought, Who are all these parents that are 30–35, have got teenagers at 40, what are they doing? Where did they learn anything? Or did they?

RML: That is the $64,000 question, isn't it? It's hard to understand all of this but it is a problem.

CHF: You mentioned, Charley, that in your own classroom you pretty much punished students who were distracted by their gadgets. How did the students respond to your insistence on that kind of discipline? Also, did you have any conversations with your teaching colleagues about that or were you a voice in the desert?

CJ: I think my colleagues appreciated what I did. The students would talk about it, but I think it worked out. We'd lose probably 60 percent of our freshmen over the next couple of years, but those that stayed with it really got with it. Then some of the kids that got away came back. I think they went away but then realized what we were talking about and what the kids that stayed understood. I was proud of that.

RML: I think part of it is that everybody is involved in so many things. I guess it is a problem of balancing out and attaching priority to the things that are most important. I have the feeling that somehow the kids are getting left out of the equation more often than they should.

CJ: I agree with you totally, the key word there being "priority." It is complicated though. I know that parents want to contribute to their community, to their church, to their neighborhoods, and the kids get left, even for a short period of time, and then they can't catch up.

RML: I hope more young people will have an opportunity to hear your message, Charley, because I think it is an important one. When the occasions arise for you to speak, I hope there are a lot of kids in the audience.

Is there anything that you would like to have the National Academy of Engineering think about from all the perspectives of your illustrious career?

CJ: I think being ready. Opportunities are going to come along for all of us. Being able to recognize them and to perform is the most important thing.

CHF: What kinds of opportunities do you foresee?

CJ: In general? Well, as technology changes, those who are knowledgeable and up to date on those particular technologies will have tremendous opportunities, with start-ups and with old companies. There are developments going on all the time. Students who know their capabilities can apply them both to the science and to getting a job.

We did a good job here at New Mexico State in getting our kids ready to interview. I can only think of two or three chemical engineering graduates who did not get a job in all these years.

RML: That is pretty remarkable. When you can place your students with ratios of that kind, that is a great credential.

CJ: We are proud of it.

Students who know their capabilities can apply them both to their field and to getting a job.

RML: How many students were in the Department of Chemical Engineering when you were head?

CJ: We averaged 95 to 105 undergraduates a year and 20 to 30 graduate students. We had 10 professors most of the time. It is twice as big now.

RML: Thinking of New Mexico reminds me that there is a lot of conversation about interim spent nuclear fuel storage facilities there. Is that something that has gotten onto your radar screen?

CJ: One of my teammates was head of the Mechanical Engineering Department and for a while he was in charge of the Carlsbad repository. Then they had a leak last year and shut it down. Now they've found a place over close to Roswell, staying in the southeastern part of the state. I don't know what is going to happen for sure; I don't think anybody does. It is still such a political football—I hate to call it football; it is more like a political soccer ball.

RML: It was a classmate of yours who was directing the Waste Isolation Project Plant?

CJ: Yes.

RML: What is his name? I have been out there many times and I might have met him.

CJ: He was interim: George Mulholland.

RML: That name does ring a bell.

CJ: His son is in charge of Boeing's NASA activities in Houston.

RML: Wow, that's interesting.

CJ: George is from Upper Darby, PA. He and a teammate of his in Upper Darby came out here, did not have any idea where they were going—like so many people back then, long time ago, thought we were still Mexico. They got here and both of them were very successful.

RML: That is great. It is interesting how, when you look at all these things over long periods of time, there are so many connections that emerge out of thin air.

CJ: That is why I say, Be ready.

RML: Your advice is well taken and this is a great demonstration of it. I want to say I enjoyed this conversation enormously. We are of the same generation so I remember watching you play when I was living in Washington and Baltimore during the 1960s and '70s.

CJ: I wasn't the best but I had more fun than anybody. I loved playing the game.

RML: It is a great game. I have a Penn State undergraduate degree and an Ohio State graduate degree so football is in my DNA.

CJ: No kidding. You got splintered from sitting in the stands before they were plastic seats.

RML: Absolutely. Joe Paterno was in his first or second year of coaching at Penn State when I was a freshman there. I typically get out to watch—they have a blue/white game in the spring, an intersquad game, and they make decisions on who is going to play where and when. I love being in crowds like those at Ohio State and Penn State and watching football. There is nothing like it.

CJ: It was something with Ohio State this year, wasn't it? Fantastic.

RML: I continue to marvel at how Cardale Jones—the third string quarterback at the beginning of the season—could win the Conference title, the Sugar Bowl, and then finally the National Championship. Must be some good coaching there!

CJ: I spoke at the Columbus Touchdown Club when I was in school, I think it was on a Friday or Saturday night, and I flew in there and I was studying—I had an exam on Monday. I was able to get the speech done, got back to the hotel, and then the airport got shut down. I was snowbound there and missed the exam and had to have a retake. I will never forget that. That was quite an experience and the fans were unbelievable. I spoke at the New York Touchdown Club and they were not nearly as nice and interested as the Columbus people were.

RML: Well, Columbus is a special place. I enjoyed being there as a student enormously. I still go back a lot. I am very much involved in some alumni things at Ohio State and at Penn State. I have a great appreciation for what they do.

CJ: It is a lot easier being here at my alma mater.

RML: Absolutely. Thank you, Charley. This has been great. I appreciate your taking the time to talk with us today.

CHF: Yes, thank you so much.

CJ: I have enjoyed the heck out of it.

RML: Good luck with your stem cell treatment. I would be really interested in knowing and following up with you just to find out how that all evolved.

CJ: Okay. I will probably know something the middle of July.

NAE News and Notes

NAE Newsmakers

Michael R. Stonebraker, adjunct professor, Massachusetts Institute of Technology, cofounder and CTO of Tamr Inc., and a researcher at MIT's Computer Science and Artificial Intelligence Laboratory (CSAIL), who has revolutionized the field of database management systems and founded multiple successful database companies, has won the Association for Computing Machinery's (ACM) **A.M. Turing Award**, often referred to as "the Nobel Prize of computing." This year marks the first time the award comes with a Google-funded $1 million prize. ACM said that Stonebraker "invented many of the concepts that are used in almost all modern database systems . . . and founded numerous companies successfully commercializing his pioneering database technology work." Dr. Stonebraker will receive the award during the ACM's annual awards banquet on June 20 in San Francisco.

Arvind, Charles W. and Jennifer C. Johnson Professor in Computer Science and Engineering in CSAIL and the Department of Electrical Engineering and Computer Science at MIT, has been elected as a **Foreign Fellow** to the **India National Academy of Sciences**.

Emery Neal Brown, Warren M. Zapol Professor of Anaesthesia at Massachusetts General Hospital, has been named a **2015 Guggenheim Fellow in Applied Mathematics**. Established in 1925, the Guggenheim Foundation has granted over $325 million in fellowships to almost 18,000 individuals, among whom are Nobel and poet laureates, Pulitzer Prize winners, Fields Medalists, and other internationally recognized honorees.

Mildred S. Dresselhaus, Institute Professor of Electrical Engineering and Physics at MIT and IEEE Life Fellow, is being honored with the **2015 IEEE Medal of Honor** "for leadership and contributions across many fields of science and engineering." She is the first woman to receive IEEE's highest award. It was established in 1917 and is presented to a candidate identified as having made a particular contribution that forms a clearly exceptional addition to the science and technology of concern to IEEE. The award consists of a gold medal, a bronze replica, a certificate, and honorarium. Dr. Dresselhaus is to receive the award at the annual IEEE Honors Ceremony on June 20 at the Waldorf Astoria Hotel in New York City.

The **2015 Marconi Prize**, considered the pinnacle honor in the field of communication and information science, will be awarded to **Peter T. Kirstein**, professor and chair of Computer Systems, University College London Engineering Sciences, whose tireless advocacy and pioneering technical contributions to computer networking helped establish and expand the Internet in Europe and many other parts of the world. Dr. Kirstein will receive the $100,000 prize at a ceremony at the Royal Society in London on October 20. "While he may not be as well known here in the US, Peter is often recognized as the 'father of the European Internet,'" says Marconi Fellow **Vint Cerf**, coinventor of TCP/IP protocol and an early collaborator with Kirstein. "But that phrase understates his contributions in the field of computer networking and in the area of protocols or systems for specific purposes. For the past 40+ years, Kirstein has made persistent contributions to the practical workings, adoption, and application of the Internet worldwide." The Marconi Prize is given each year to one or more scientists and engineers who, like radio inventor Guglielmo Marconi, achieve advances in communications and information technology for the social, economic, and cultural development of all humanity.

The annual **Global Energy Prize** honors outstanding achievements in energy research and technology that are helping address the world's pressing energy challenges. Founded in 2002, it is awarded to the most accomplished minds in the research world. Honorees receive a gold medal from the president of Russia at the International Economic Forum in St. Petersburg. The award also comes with a cash prize of 33 million rubles, equivalent to about $645,000. This year **Shuji Nakamura**, a professor in the Materials Department at the University of California, Santa Barbara, and **B. Jayant Baliga**, director of the Power Semiconductor Research Center at North Carolina State University, will share the prize. Dr. Nakamura is being recognized for the invention, commercialization, and development of energy-efficient white LED lighting technology. He won the Nobel Prize in physics last year for inventing the blue LED. Dr. Baliga, lauded by *Scientific American* as one of the heroes of the semiconductor revolution, is being honored for the invention, development, and commercialization of the insulated gate bipolar transistor, an important innovation for the control and distribution of energy.

NAE Honors 2015 Draper and Russ Prize Winners

The NAE honors outstanding individuals for significant innovation, leadership, and advances in bioengineering. The 2015 winners of the Charles Stark Draper Prize for Engineering and the Fritz J. and Dolores H. Russ Prize were honored at a black-tie dinner on February 24 at the National Academy of Sciences in Washington, DC. The recipients accepted their awards before an audience of more than 170 guests, with NAE president **C. D. Mote, Jr.** at the podium. Also assisting in the presentations were Kaigham (Ken) J. Gabriel, president and CEO of the Charles Stark Draper Laboratory, and Roderick J. McDavis, president of Ohio University.

Charles Stark Draper Prize for Engineering

Left to right: Kaigham (Ken) J. Gabriel, Tetsuya Takeuchi (accepting for Isamu Akasaki), Phyllis M. Wise (accepting for Nick Holonyak, Jr.), Russell D. Dupuis, Shuji Nakamura, M. George Craford, and C. D. Mote, Jr.

Nick Holonyak, Jr., M. George Craford, **Russell D. Dupuis**, **Isamu Akasaki**, and **Shuji Nakamura** were awarded the 2015 Charles Stark Draper Prize for Engineering "for the invention, development, and commercialization of materials for processes for light-emitting diodes (LEDs)."

LEDs produce the greatest amount of light for the energy used and have the longest lifetime of any lighting source available. They are used by billions of people on a daily basis in computer monitors, cellphone screens, TVs, traffic lights, home lighting, digital watch displays, medical applications, and many more.

The $33 billion LED industry has stimulated global job growth and dramatically lowered the cost of energy for lighting. In 2012 alone, more than 49 million LEDs were installed in the United States, with an estimated annual savings in energy costs of $675 million, and in 2013 LEDs in general lighting applications reduced US CO_2 emissions by more than 12 million tons.

Nick Holonyak, Jr. is considered the father of the visible LED. His invention of the visible red LED in 1962 at General Electric initiated the broad use of III-V semiconductor alloy technology, ultimately impacting lives everywhere. The long-life red LED was initially used for panel indicators, traffic lights, and automobile taillights. As other colors developed, applications broadened for low-power illumination and decorative applications.

Dr. Holonyak's breakthrough work in developing III-V semiconductor alloys was a key factor in the invention of the visible LED and led to the commercial introduction of red gallium arsenide phosphide (GaAsP) LEDs and eventually to the concept of an "ultimate lamp." In the 1970s he developed the first quantum well (QW) semiconductor laser and demonstrated the first room-temperature continuous wave operation of a QW diode laser (with Dupuis). Today, every LED and semiconductor laser incorporates his work, as the alloys are the basis for other LED colors and the QW diode laser is commonly used in CD and DVD players.

George Craford has been a leader in the development and implementation of LED technology for nearly 50 years. At Monsanto Chemical, he led the development of a new GaAsP doped with nitrogen (GaAsP:N) LED technology, which yielded the first yellow LED, improved the performance of red LEDs, and became the dominant high-performance LED technology for more than a decade.

He moved on to Hewlett-Packard and became technology manager for the Optoelectronics Division, responsible for maintaining leadership in LED technology. His team pioneered the development of another new LED technology that utilized the quaternary compound aluminum gallium indium phosphide (AlInGaP) and yielded the world's highest-performance red, orange, and amber LEDs as well as the first LED with performance of 100 lumens per watt, which is the type used in traffic lights, automobiles, and many other applications today. In 1990 he became chief technology officer of what is now Philips Lumileds Lighting Company, overseeing the development of the first high-power white LEDs, widely used in many types of lighting including general illumination, automobile headlights, and cellphone flash. The company remains at the forefront of LED technology.

In 1977 Russell Dupuis developed the metalorganic chemical vapor deposition (MOCVD) materials growth process, an electronically controlled method for growing the crystals in LEDs that is used today for the commercial production of LEDs. His technology is the basis of virtually all production of high-brightness LEDs as well as laser diodes (LDs), solar cells, and high-speed optoelectronic (light-controlling) devices.

With decades of research, Isamu Akasaki's efforts have resulted in the technology behind today's advanced entertainment devices, high-brightness display lighting, and white illumination sources. During the late 1960s he began researching solutions to the roadblocks that prevented realization of high-performance blue LEDs and LDs. In 1985 he and his group at Nagoya University made multiple achievements in gallium nitride (GaN)–related technology that ultimately led to the development of GaN as the wide-bandgap semiconductor system to enable the new light source. His work came to fruition in the 1990s with pioneering developments that led to high-brightness blue, green, and white LEDs and high-performance blue-violet semiconductor lasers.

Dr. Akasaki's research and achievements have influenced all subsequent developments of these LEDs and LDs, enabling devices such as the Blu-ray disc player, white illumination sources, and solid state full-color displays. Additionally, his work in the 1990s demonstrated stimulated emission in the ultraviolet region with optical excitation from GaN at room temperature and electric current–injected stimulated-emission ultraviolet/purple-blue LDs. His inventions launched a new market for optoelectronic devices, and the Akasaki Institute at Nagoya University was founded in 2006 based on royalties from his patents.

Shuji Nakamura began research on blue LEDs and ultimately developed the first group III nitride-based blue-green LEDs and violet LDs. His development of nitride-based semiconductors represents one of the most important achievements in semiconductor materials science in the last 30 years. His research on p-type doping in gallium nitride and efficient indium gallium nitride (InGaN) double-heterostructure LEDs was key in developing high-brightness blue, green, and white LEDs as well as blue LDs, which have enabled energy-efficient LED lighting and displays. He went on to develop InGaN films of the highest crystal quality, enabling the realization of bright blue double-heterostructure light-emitting devices. These achievements are evident today in energy-efficient solid state lighting, displays, medicine, and the next generation of Blu-ray optical storage.

Acceptance Remarks by M. George Craford

M. George Craford

It is a privilege for me to represent my colleagues here at the podium tonight. We thank the NAE and everyone connected with the Draper Prize for honoring us with this amazing award. We also thank our wives and families who have tolerated our absence over many years while we have been out chasing photons of various colors. And we want to thank our coworkers. Much of the work we have done, in fact nearly all of the work of this type, is done by teams. Without our coworkers this work would not have been possible. We are sorry that Professors Akasaki and Holonyak could not be with us tonight. Professor Dupuis and I were students of Professor Holonyak, who earlier had been a student of the great John Bardeen, both of them at the University of Illinois.

The demonstration by Holonyak in 1962 that red LEDs and lasers could be fabricated from compound semiconductor alloys drove the solid state lighting revolution. It was the beginning. All of today's high-performance LEDs are compound semiconductor alloys.

Holonyak also predicted in 1963 that his work would lead to solid state lighting, but that much more experimental work would be needed. That additional work has taken over 50 years and is still going. The work has taken many forms, including working with new semiconductor alloys to achieve different colors and growing increasingly complex semiconductor structures to improve efficiency. Nanometer-scale layers and quantum wells were used by LED engineers long before "nanotechnology" became a popular buzzword.

My contribution, working with others, was to pioneer the yellow LED and to improve the efficiency of red and yellow devices. Professor Dupuis developed MOCVD, the growth technology that is used for the production of all types of LEDs. Professors Akasaki and Nakamura developed high-efficiency blue LEDs, which, when combined with yellow down-converter phosphor, yield white LEDs that provide solid state lighting. Professor Nakamura also developed the blue laser diode, which is now finding applications in headlights.

Early LEDs were barely visible in a lighted room but today they are 1,000 times more efficient and still getting brighter. This year the Super Bowl was illuminated by LED floodlights. All of general illumination is changing from conventional illumination to LEDs. Even in third world countries LEDs combined with solar cells lengthen the day by providing illumination for schoolchildren and adults who previously had only fire.

Conventional lighting technology has lasted around 100 years. Solid state lighting is expected to last much, much longer. In fact, in an article in the *American Journal of Physics* in September 2000 Holonyak argued that LEDs are the ultimate lamp. There is no end in sight for solid state lighting.

Thank you again for recognizing us for our contribution to this ongoing worldwide engineering effort.

Fritz J. and Dolores H. Russ Prize

The 2015 Fritz J. and Dolores H. Russ Prize is awarded to Graeme J. Clark, Erwin Hochmair, Ingeborg J. Hochmair-Desoyer, Michael M. Merzenich, and Blake S. Wilson "for engineering cochlear implants that enable the deaf to hear."

Cochlear implants are small electronic devices that provide a sense of sound to people with severe to profound sensorineural hearing loss. The quality of that sound differs from natural hearing, with less sound information received and processed by the brain, but many hearing-impaired people are able to hear and understand speech and environmental sounds. Newer devices and processing strategies allow the hearing impaired to hear better in noisy settings, enjoy music, and even swim with their implants. More than 320,000 hearing-impaired people around the world have received cochlear implants—they are the most-used neural prosthesis developed to date.

Left to right: Roderick J. McDavis, Blake S. Wilson, Michael M. Merzenich, Erwin Hochmair, Ingeborg J. Hochmair-Desoyer, and C. D. Mote, Jr.

The lives of hundreds of thousands of people around the world with severe to profound hearing loss have been transformed with the help of Graeme Clark's groundbreaking research. Inspired by his own father's hearing loss, Dr. Clark spent years on research that led to the development of the first multiple-channel cochlear implant (CI), clinically approved by the US FDA in 1985, enabling speech understanding in profoundly deaf people. His research also demonstrated that the implant provided effective speech perception and language in profoundly deaf children—the first major advance since the development of sign language.

The implant also represented another important first: the first prosthesis to use electronic technology to replace a human sense—the sense of hearing and understanding speech. And Dr. Clark was the first to establish the benefits of both bilateral cochlear implants and, alternatively, an implant in one ear with a hearing aid in the other.

Erwin Hochmair began research on CIs in 1975, with Ingeborg Desoyer (now Ingeborg Hochmair-Desoyer). Two years later their work led to the world's first microelectronic multichannel CI surgery, in Vienna. They continued their research at Stanford University and in the 1980s were consultants for 3M in St. Paul. Together they established the MED-EL Company in Innsbruck in 1989; it is now the world's second largest CI manufacturer and a worldwide leader in implant technology, working toward developing further technological advances for hearing implant systems.

The first woman to win the Fritz J. and Dolores H. Russ Prize, Dr. Hochmair-Desoyer began her career in 1975 as a research assistant and, together with Erwin Hochmair, based on existing knowledge of auditory physiology combined with an engineering-based approach, developed the first microelectronic multichannel CI, implanted in 1977.

Michael M. Merzenich led a research team that established important neurophysiological underpinnings and addressed fundamental engineering issues related to the designs of multichannel cochlear implants. His team's research paved the way to the development of a highly versatile multichannel CI successfully commercialized by Advanced Bionics Corporation.

Acceptance Remarks by Ingeborg J. Hochmair-Desoyer

Ingeborg J. Hochmair-Desoyer

The Fritz J. and Dolores H. Russ Prize recognizes a bioengineering achievement in widespread use that improves the human condition. This achievement should *create for good* at the highest level, helping the public better understand and appreciate the contributions of engineers to our health, well-being, and quality of life.

In the name of the five recipients of this prize for engineering CIs that enable the deaf to hear, and in the name of many others who contributed to the development of the CI to the status it has now, I would like to thank the committee, Ohio University, and the NAE for selecting the CI for this year's Russ Prize! All five of us have worked on CIs for decades and are very passionate about this field, and the CI is indeed a very special development: It is the first replacement of a human sense, the sense of hearing!

The aims of the Russes are fulfilled

with this device in a very visible way: users of CIs typically wear their audio processors all waking hours in order to hear and understand and enjoy sound. The CI has to do with communication, with being able to take part in society. It is connected with every child's human right for education, and there is a growing body of evidence that it can alleviate isolation and cognitive decline in older adults.

All of this year's Russ Prize recipients, from different parts of the world, have in common that they developed university-built prototypes of cochlear implants and improvements of their features with pioneer patients, which after many years of engineering and research ultimately resulted in today's widely spread cochlear implants provided by the three biggest CI manufacturers, in Australia, Europe, and the United States.

In 2014 approximately 55,000 CIs were implanted around the globe. This is a big number but still much smaller than the cardiac pacemaker, which was recognized with the first Russ Prize in 2001 and where the annual numbers far exceed a million per year. While in most highly developed health systems almost all children born deaf or with a considerable hearing loss do in fact receive a CI before the age of 5, at around which the period of plasticity ends, this is not the case around the world yet, and there is also a huge unmet need with every age group in acquired deafness, especially in older adults.

Deafness is very common, almost every family is affected. Since this piece of engineering, the cochlear implant, is available, I would like to urge everyone who does not hear to his or her satisfaction to do something about it—try a hearing aid, get it fitted and refitted, and if it is not sufficient try hard to get a hearing implant, a cochlear implant. Poor hearing is too big a barrier to communication and quality of life to accept it easily.

Thank you again!

Bernard M. Gordon Prize for Innovation in Engineering and Technology Education

Left to right: Joseph E. Aoun, Simon Pitts, Bernard M. Gordon, Michael B. Silevitch, and C. D. Mote, Jr.

On April 10 Simon Pitts and Michael B. Silevitch accepted the 2015 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education, awarded to Northeastern University "for developing an innovative method to provide graduate engineers with the necessary personal skills to become effective engineering leaders." NAE president **C. D. Mote, Jr.**, presented the awards, joined onstage by **Bernard M. Gordon**, BMG Charitable Trust, and Joseph E. Aoun, president of Northeastern University. The presentation concluded with remarks from Dr. Aoun. The public Gordon Prize lecture will take place during the 2015 NAE Annual Meeting on Sunday, October 4.

The Northeastern University Gordon Engineering Leadership Program (GEL) is a graduate degree and certificate program designed to develop leadership skills for the practicing engineer. Its curriculum focuses on five core pillars: leadership capabilities, leadership labs, product development, scientific foundations, and a challenge project. The program brings together teams of students, who typically have three to five years of work experience in the field, to learn how to tackle challenges through rich discussion and mutual learning.

Simon Pitts, director of the GEL program, has been instrumental in building a community of practitioners among universities to share best practices in engineering leadership development. Before joining the program, he was a senior executive at Ford Motor Co., where he learned the value of hiring engineers with diversified backgrounds and the leadership capabilities necessary to deliver successful products to market. His professional background and dedication to cultivating meaningful relationships between students and industry have had a tremendous impact on the growth and success of the GEL program.

Michael B. Silevitch, Robert D. Black Professor of Engineering, created the GEL program and was its initial director. He is now a lead mentor for students in the program. A critical element of the GEL curriculum is "three-way mentoring": each student is assigned a mentor from the program, one from an industry partner, and one with expertise in the student's technical area. Silevitch has been critical to advancing this part of the program, which is designed to help students improve their leadership skills through evaluations from their mentors.

Acceptance Remarks by Simon Pitts

Simon Pitts

Michael and I are greatly honored to receive the 2015 Gordon Prize from the National Academy of Engineering. Our sincere appreciation goes to NAE president Dr. **Dan Mote**, executive officer Dr. **Al Romig**, and all those at the National Academy of Engineering. Our sincere appreciation also goes to **Bernie Gordon**, for making this award possible, and to members of the Gordon Prize Selection Committee, represented here today by Dr. **Sam Fuller**.

We would also like to recognize the team of dedicated and talented individuals with whom we have collaborated to develop and execute the engineering leadership education that we deliver. I will mention two people who do an amazing amount of heavy lifting to teach the majority of the program content: Colonel Steve McGonagle and Professor Steve Klosterman.

I cannot name all the others that make vital contributions to the program, so, collectively, *thank you* to all the others that teach, the staff that enable the program, the Gordon Mentors who ensure that the education of each student meets both the needs of the student and the goals of the program, and the faculty advisors who are key in providing detailed academic knowledge and insight to enable the challenge projects to have value for the students and companies. I would also like to thank the current candidates and the graduated Gordon Fellows for fully engaging in the program.

The personal growth that we see in the 12 months that the candidates are in the program never fails to astound me and we appreciate the effort that you all invest to achieve these results.

This award recognizes our engineering leadership program as an innovation in providing a systematic way to develop both the character and the technical skills needed to lead engineering teams to successfully deliver in a challenging real world environment.

Northeastern University is uniquely suited to providing the environment where this type of educational innovation can flourish. With our inbuilt DNA of experiential learning through co-op and our focus on use-inspired research, it is a natural fit to combine faculty with deep industry and academic knowledge to deliver a program that educates how to successfully lead engineering teams to deliver products to markets, make companies and organizations successful, and thereby benefit society. We are proud that the program is accelerating the careers of the fellows that have passed through it and is having an impact.

Michael and I feel that this prize is, in addition to being a tribute to the team, recognition of the value that we are delivering with our innovation. We thank you for this award.

Foreign Secretary and Councillors Elected

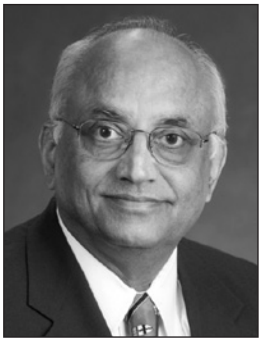

Ruth A. David

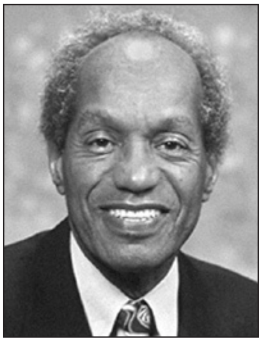

Wanda A. Austin


Richard H. Truly


Anita K. Jones


John L. Anderson


Venky Narayanamurti


Arnold F. Stancell

This spring the NAE elected its foreign secretary, reelected three incumbent councillors, and elected a new councillor. All terms begin July 1, 2015.

Elected to a four-year term as NAE's foreign secretary was **Ruth A. David**, recently retired president and chief executive officer of Analytic Services Inc. (ANSER). **Wanda A. Austin,** president and chief executive officer of the Aerospace Corporation; **Anita K. Jones**, university professor emerita at the University of Virginia; and **Richard H. Truly**, retired vice admiral in the United States Navy and retired director of the National Renewable Energy Laboratory, were reelected to three-year terms as councillors. Newly elected to a three-year term as councillor was **John L. Anderson**, president of Illinois Institute of Technology.

On June 30, 2015, **Venkatesh "Venky" Narayanamurti** completes a four-year term of service as foreign secretary and **Arnold F. Stancell** completes six continuous years of service as councillor, the maximum allowed under the Academy's bylaws. In May, Dr. Narayanamurti and Dr. Stancell were recognized for their distinguished service and other contributions to the NAE.

2015 German-American Frontiers of Engineering Held in Potsdam, Germany

The 2015 German-American Frontiers of Engineering Symposium (GAFOE) was held April 15–18 at the Steigenberger Hotel Sanssouci in Potsdam, Germany. The NAE partners with the Alexander von Humboldt Foundation to organize this event, the longest-standing bilateral FOE program, started in 1998. The symposium organizing committee was cochaired by NAE member **Cynthia Barnhart**, chancellor and Ford Professor of Engineering in the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology, and Peter Moser, head of innovative power plant technology R&D at RWE Power AG.

Modeled on the US Frontiers of Engineering Symposium, GAFOE brings together engineers ages 30–45 from German and US companies, universities, and government. The goal of the meeting is to convene emerging engineering leaders in a forum where they can learn about leading-edge developments in a range of engineering fields, thereby facilitating an interdisciplinary transfer of knowledge and methodology. In the case of the bilateral FOE symposia, there is the added dimension of helping build cooperative networks of younger engineers across national boundaries.

At this year's GAFOE the four session topics were Nano-to-Micro Robotics, Particle Accelerators and their Applications, Synthetic Membranes and their Applications, and Protecting User Privacy in the Age of Big Data. A program, list of attendees, and presentation slides are posted at the GAFOE link at www.naefrontiers.org.

The session on Nano-to-Micro Robotics reported applications for millimeter-sized robots—and smaller—in medicine, manufacturing, and search and rescue. Mobile robots and robotic assembly at these size scales must overcome many challenges related to their fabrication, control, and power delivery. The first two speakers focused on nanoscale robotics and assembly—specifically, molecular motors as a potential driver for nanorobots and DNA origami for assembly of nanoscale objects. Presentations in the second half of the session covered microscale robotics: nanorobot propulsion in biological fluids and microfabricated robotic components approaching millimeter scales.

The organizers of the session on applications of particle accelerators sought to answer the question: How can the knowledge and technological progress provided by accelerator physics best be used to benefit society? Applications include medical diagnostics, food sterilization and packaging, tracing of groundwater migration patterns, and analysis of mechanical wear in novel materials. The first part of the session focused on cutting-edge magnet design for scientific and medical accelerator applications and superconducting accelerator technology for large-scale facilities. The next two speakers introduced the generation of laser-driven ion and X-ray beams and described their applications.

Well-known membrane applications include filtration of particles, colloids, or molecules from liquids or gas streams, water purification,

Participants in the 2015 German-American Frontiers of Engineering recovery of organic vapors in the petrochemical industry, and medical uses for artificial kidneys or lungs. The session on synthetic membranes and their applications showed how these membranes can save energy compared to established industrial processes, improve human health, and possibly make paradigm-changing contributions to future energy supply. The first speaker explained the general principles of membrane technology and challenges associated with manufacturing and industrial upscaling. This was followed by talks on efficient gas separation with inorganic membranes, liquid electrolytes and solid membranes in new battery systems, and ways that membrane technology contributes to sustainability and the life sciences.

The final session, on protecting user privacy in the age of big data, pointed out that Internet surveillance and other technologies to gather user information have made the protection of user privacy a priority. In addition to surveillance, various organizations and countries are developing mechanisms to control users' access to information, through either explicit censorship or more subtle forms of information manipulation. The talks in this session focused on threats to user privacy such as user tracking and information control on the Internet as well as technologies that protect user privacy and the usability of these solutions by laypeople.

Helmut Schwarz, president of the Alexander von Humboldt Foundation, and NAE president **C. D. Mote, Jr.**, spoke at the welcome dinner. On the first afternoon there were flash poster talks followed by a poster session in which attendees presented their research or technical work to each other. The posters, displayed throughout the meeting, prompted many ongoing conversations. On the second afternoon, the group took a walking tour of the grounds of the Sanssouci Palace adjacent to the hotel, followed by a bus tour of Potsdam and dinner at the restaurant Braumanufaktur Forsthaus Templin, a craft beer brewery near Potsdam.

Funding for the meeting was provided by The Grainger Foundation and the National Science Foundation. The next GAFOE meeting will be held in 2017 in the United States.

NAE has additional bilateral Frontiers of Engineering programs with Japan, India, China, and the European Union. All FOE meetings bring together outstanding engineers from industry, academe, and government at a relatively early point in their careers (participants are 30–45 years old) and provide an opportunity for them to learn about developments, techniques, and approaches at the forefront of fields other than their own, something that has become increasingly important as engineering has become more interdisciplinary. The meeting also facilitates the establishment of contacts and collaboration among the next generation of engineering leaders. For more information about this activity, visit www.naefrontiers.org or contact Janet Hunziker in the NAE Program Office at jhunziker@nae.edu.

North Carolina State University and NAE Hold Symposium: "The Continuum from Tissue Engineering Through Regenerative Medicine to Rehabilitation Engineering"

An NAE regional meeting was held in conjunction with a symposium on developments in tissue engineering, hosted by the North Carolina State University (NC State) on March 17, 2015. Dean Louis Martin-Vega welcomed the guests and summarized the unique opportunities for bioengineering at NC State and in North Carolina. Chancellor Randy Woodson recognized the honor that the NAE brought to NC State, thanked the organizers, and introduced NAE president **C. D. Mote, Jr.** Dr. Mote explained that the regional meeting was part of an outreach effort by the NAE, and encouraged the students in the audience to pursue their engineering careers.

In the first presentation Victor J. Dzau, president of the Institute of Medicine, reviewed recent advances in repairing heart tissue, summarized the shortfalls of current approaches to stem cell therapy, and talked about what the future might hold. Xian-En Zhang, professor of the Wuhan Institute of Virology in the Chinese Academy of Science and past director general of basic research and technology in China's Ministry of Science and Technology, provided a comprehensive review of stem cell research in China, stressing the partnerships being formed with the United States. In the next talk, on engineering new regenerative therapies for arthritis, Farshid Guilak, director of orthopedic research at Duke University Medical Center, noted that new regenerative therapies for arthritis are beginning to show positive results in animals, but significant hurdles must be addressed for such therapies to be widely used in humans.

Anthony Atala, director of the Wake Forest Institute for Regenerative Medicine, described successes in the ability to create organs and tissues, with further discussion of expanding the technology to create increasingly complex three-dimensional constructs. The testament of one of his patients highlighted the importance of his research. Ke Cheng, associate professor at the College of Veterinary Medicine at NC State, showed data on cardiac tissue repair using stem cell therapies that did not require ex vivo stem cell culture, suggesting practical solutions to many of the problems raised by Dr. Dzau.

The final presentation on rehabilitation engineering was by Helen Huang, director of the Rehabilitation Engineering Center at UNC-Chapel Hill and NC State. She explained the crucial importance of volitional control of prostheses, as in, for example, the need to walk without conscious thought. She used videos to demonstrate how nerves can be wired through muscles and sensors to guide the movement of a robotic arm or leg from thought to action.

The sessions were moderated by NAE councillor **Fran Ligler**. At the conclusion of the program, she invited the guests and speakers to a reception on the balcony of the technology award–winning Hunt Library overlooking Lake Raleigh.

NAE Regional Meeting Hosted by University of Washington College of Engineering: "Reverse Engineering the Brain"

On March 19, NAE members and other guests in Washington state and the northwest region gathered at the University of Washington (UW) in Seattle to learn about the latest developments in neuroengineering at the NAE regional meeting and symposium. The event was hosted by the UW College of Engineering and sponsored by the NSF Research Center for Sensorimotor Neural Engineering (CSNE), the university's Institute of Neuroengineering (UWIN), and the Allen Institute for Brain Science.

NAE president **C. D. Mote, Jr.** addressed 30 NAE members at a luncheon and business meeting hosted on campus. The members then joined UW faculty, students, and staff, and industry professionals at the symposium, where Michael B. Bragg, Frank and Julie Jungers Dean of Engineering; Dr. Mote; and **Matthew O'Donnell**, Frank and Julie Jungers Dean Emeritus and professor of bioengineering, delivered welcoming remarks.

The symposium's 140 registrants were introduced to work being done on the UW campus and in the Puget Sound region. Dr. O'Donnell spoke about cutting-edge research that expands understanding of the brain to the molecular level and will enable the design of neural systems and technologies that can provide groundbreaking medical solutions. Three speakers then showcased their research in these areas.

Joshua R. Smith, associate professor of computer science and engineering and electrical engineering at the UW, presented his efforts to create the next generation of implanted electronic systems that can record neural activity, perform computation to evaluate the signals associated with this activity, generate commands to modulate organ function, and communicate with physicians. He explained how reverse engineering the brain can reveal a lot about building energy-efficient systems inside the body. Implanted deep brain stimulators have the potential to address diseases such as Parkinson's disease, tremors, dystonia, chronic pain, depression, and obsessive compulsive disorders.

Elizabeth A. Buffalo, associate professor of physiology and biophysics at the university, described her work on spatial representations, eye movements, and oscillatory neural activity in the primate hippocampal formation that may contribute to spatial and mnemonic representations in the medial temporal lobe. By studying neural mechanisms for space and memory in primates and rats, she hopes to achieve breakthroughs that can be applied to memory disorders as well as Parkinson's, depression, dystonia, and essential tremor.

Nuno Maçarico da Costa, assistant investigator at the Allen Institute for Brain Science, reviewed current efforts to understand the different components of the mouse neocortex, including the architecture of its circuits and their relationship with function.

The day ended with a panel discussion moderated by Dr. O'Donnell. Panelists Rajesh Rao, director of the Center for Sensorimotor Neural Engineering and professor of computer science and engineering; Adrienne Fairhall, codirector of UWIN and associate professor of physiology and biophysics; and Dr. da Costa addressed applications in neural engineering, tools needed to effectively reverse engineer the brain, alternatives to brain implants, and collaboration with artificial intelligence applications that share many of the underlying principles of neural engineering but use different tools.

2015 Convocation of Professional Engineering Societies

The 2015 Convocation of Professional Engineering Societies took place April 20–21 in Washington. The topic of the morning session on the 20th was "Big Data Insights into Complex Sociotechnical Systems," moderated by NAE executive officer **Alton D. Romig, Jr.** The first talk, "The Promise of Big Data for Civic Engineering," was given by **Steve E. Koonin**, director of the Center for Urban Science and Progress at New York University. Marta C. Gonzalez, an associate professor in the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology, followed with a presentation on "Discovering Basic Mechanisms of Human Daily Behavior with Mobile Phone Data." A very different perspective on the applications of big data was provided by Tanzeem Choudhury, associate professor of information sciences at Cornell University: she explained approaches for "Tracking Behavioral Symptoms of Mental Illness Using Automated Sensing and Delivering Personalized Interventions Using Smartphones." The panel's closing presentation, "Human Responses to Engineered Systems: Case Studies from Financial, Health, and Urban Systems," was delivered by Michael Pennock, assistant professor in the School of Systems & Enterprises at Stevens Institute of Technology.

The keynote speech after lunch was a very entertaining presentation by 2015 Norm Augustine Award Winner Suveen N. Mathaudhu, an assistant professor in the Department and Materials Science and Engineering at the University of California, Riverside. Citing familiar Marvel Comics figures he explained, both colorfully and effectively, that "With Great Power Comes Great Responsibility: Lessons from Superheroes (and Supervillains) for the STEM Community."

The afternoon session, moderated by Patrick J. Natale, vice president for business strategies at Hatch Mott MacDonald, was about "Supporting Re-Entry and Alternative Career Paths into the Engineering Workforce." Jayne B. Morrow, executive director of the National Science and Technology Council, Office of Science and Technology Policy, led off with her talk "Supercharging Re-entry of Women in STEM." Turning to another underrepresented group, David T. Hayhurst, dean of the College of Science and Technology at the University of Southern Mississippi, described efforts toward "Assuring a Successful Transition for Veterans to an Engineering Career." Additional measures were set forth by Zenaida Otero Gephardt, an associate professor in the Department of Chemical Engineering at Rowan University, in her talk "AIChE-W2R2 (Women Workplace Retention and Reentry) Initiatives: A Template for Professional Society Initiatives Development." Nick Desport, deputy executive director of the Society of American Military Engineers, explained challenges and opportunities for "Transitioning Veteran Engineers." Next, Jennifer Howland, the executive of IBM's Pathways Program, explained its "Pathways for Experienced Technical Women." The panel's final speaker was Bill Kmetz, CH2M Hill chief security officer and cochair of the Veteran Employee Network, who described the company's "Partnerships and Employee Networks" for hiring.

That evening the AAES honored seven outstanding engineers. **Jeffrey Wadsworth**, president and CEO of Battelle Memorial Institute, was selected for the National Engineering Award, presented for "inspirational leadership and tireless devotion to the improvement of engineering education and to the advancement of the engineering profession as well as to the development of sound public policies as an engineer-statesman." The John Fritz Medal went to Jon D. Magnusson, PE, senior principal of Magnusson Klemencic Associates; the medal is awarded for "scientific or industrial achievement in any field of pure or applied science." The Honorable James A. Rispoli, PE, former assistant secretary of energy, received the Kenneth Andrew Roe Award, which recognizes "an engineer who has been effective in promoting unity among the engineering societies." As mentioned above, the Norm Augustine Award for Outstanding Achievement in Engineering Communications was presented to Suveen N. Mathaudhu; the award recognizes "an engineer who has demonstrated the capacity for effectively communicating the excitement and wonder of engineering… who can speak with passion about engineering—its promise as well as its responsibility—so that the public may have…a better appreciation for how engineers improve our quality of life." **Diran Apelian**, director of the Metal Processing Institute at Worcester Polytechnic Institute, was awarded the Joan Hodges Queneau Palladium Medal, which is presented on behalf of the National Audubon Society to honor "an engineer who encourages cooperation between engineering professionals and environmentalists to create innovative solutions to environmental problems." For "outstanding reporting of an event or issue that furthers public understanding of engineering," John Hockenberry, of New York Public Radio, received the AAES Engineering Journalism Award. Former ASCE executive director Patrick J. Natale was honored with the AAES Chair's Award.

The next morning participants convened on Capitol Hill in the Rayburn House Office Building for the Annual Engineering Public Policy Symposium; this year's topic was "Big Data, Energy, and Manufacturing: Policy Priorities for the 1st Session, 114th Congress." Attendees heard from Thomas Kalil, deputy director for policy for the White House Office of Science and Technology Policy; Suzanne Iacono, acting assistant director of NSF's Computer and Information Science and Engineering Directorate, and Irene Qualters, director of NSF's Division of Advanced Cyberinfrastructure; and a panel on manufacturing policy that included **Erik Antonsson**, corporate director of technology at the Northrop Grumman Corporation and a member of the NAE committee that authored the recent report *Making Value for America: Embracing the Future of Manufacturing, Technology, and Work*. Funding for the symposium was provided by the United Engineering Foundation.

The two-day event ended with the AAES General Assembly meeting, held in the NAS Building from 2:00 to 5:00.

Next year's convocation will take place April 18–19, again at the NAS Building in Washington.

Report and Toolkit from NAE-Sponsored Diversity Summit

NAE member Linda Abriola and summit participants.

A summit on Diversity in the Minerals, Metals, and Materials Professions (DMMM1), cosponsored by the Minerals, Metals, and Materials Society (TMS) and National Academy of Engineering, was held July 29–31, 2014, at the National Academy of Sciences Building in Washington. Approximately 120 attendees, spanning all career stages and representing government, academia, and industry, discussed what does and does not work well in a professional environment and shared strategies for managing and mitigating diversity issues in the workplace.

An important goal was to capture the valuable content developed at the summit in outputs that would live well beyond the meeting. The *DMMM1 Final Report: Thinking Globally* and the *DMMM1 Toolkit: Acting Locally* are now available at www.tms.org/DiversityReport.

The report identifies five common themes related to diversity and inclusion issues in workplace environments and sectors—mentorship, work-life balance, community, awareness, and vigilance—and focuses on actionable strategies for workplace issues in these areas. The toolkit provides resources to address these issues.

"NAE hosted the summit…[and made] it possible to convene a wide cross-section of participants in a setting conducive to discussion and collaboration on important topics," said James J. Robinson, TMS executive director. "Sharing the information and experiences discussed at the summit through the report and toolkit will encourage even broader participation and action on diversity and inclusion in the science and engineering work environment. The creation of these resources would not have been possible without the generosity and foresight of NAE."

In addition to cosponsoring the summit, the NAE participated in the development of the programming and outcomes. **Tresa M. Pollock**, University of California, Santa Barbara, was a summit advisory organizer, and the following NAE members were speakers and panel discussants: **Linda Abriola**, dean, School of Engineering, Tufts University; **Corale Brierley**, Brierley Consulting LLC; **Mildred Dresselhaus**, Massachusetts Institute of Technology; and **Julia Phillips**, Sandia National Laboratories.

Calendar of Meetings and Events

May 4	Making Value for America: Embracing the Future of Manufacturing, Technology, and Work Federal Reserve Bank of Chicago
May 7–8	NAE Council Meeting
June 1–3	China-America Frontiers of Engineering Beckman Center Irvine
June 2–3	Committee on Women in Science, Engineering, and Medicine Meeting Beckman Center Irvine
June 8	NAE Awards Committee Conference Call
June 11	First 2016 Gordon Prize Committee Meeting
June 23	Frontiers of Engineering Education Planning Meeting Chicago
June 23–24	Concussion: A National Challenge: NAE Regional Meeting Case Western Reserve University Cleveland
June 24–25	NRC-NAE Skilled Technical Workforce (Middle Skills) Committee Meeting
June 30	NAE E4U2 Video Contest Judges Committee Meeting
July 16	First 2016 Draper Prize Committee Meeting
August 2–3	NAE Council Meeting Woods Hole, Massachusetts
September 9–11	US Frontiers of Engineering Beckman Center Irvine
September 10	2016 Gordon Prize Final Committee Meeting
September 14–16	CAE-NAE-RAE Global Grand Challenges Summit Beijing
September 18	Deadline for Submission of Exemplary Engineering Ethics Education Activities

All meetings are held in National Academies facilities in Washington, DC, unless otherwise noted.

In Memoriam

CHARLES A. AMANN, 88, retired research fellow, General Motors Corporation, died on March 10, 2015. Mr. Amann was elected to the NAE in 1989 for contributions to the analytical literature of heat engines of all types and leadership in furthering the understanding of such engines.

RUPERT L. ATKIN, 96, retired vice president, Engineering Automotive Worldwide, TRW Inc., died on December 11, 2014. Mr. Atkin was elected to the NAE in 1975 for contributions to automotive safety and vehicle control, including steering, wheel and brake, and skid control systems.

A. JAMES CLARK, 87, chair and chief executive officer, Clark Enterprises Inc., died on March 20, 2015. Mr. Clark was elected to the NAE in 2005 for the development of project controls and construction equipment, the creation of a major construction firm, and support for engineering education.

JOHN P. CRAVEN, 90, retired president, Common Heritage Corporation, died on February 12, 2015. Dr. Craven was elected to the NAE in 1970 for contributions to the development of sea-based deterrence, deep-submergence vessels, and ocean technology.

ROBERT G. DEAN, 84, professor emeritus of coastal engineering, University of Florida, died on February 28, 2015. Dr. Dean was elected to the NAE in 1980 for contributions to field, laboratory, and analytical researches clarifying wave, erosion, and coastal processes developing relevant analytical procedures.

THOMAS F. DONOHUE, 84, retired division staff engineer, GE Aircraft Engines, died on October 25, 2014. Mr. Donohue was elected to the NAE in 1994 for contributions to aerothermodynamic design of advanced aerospace propulsion systems.

FLOYD DUNN, 90, professor emeritus of electrical engineering, of biophysics, and of bioengineering, University of Illinois at Urbana-Champaign, died on January 24, 2015. Dr. Dunn was elected to the NAE in 1982 for contributions to fundamental knowledge of ultrasonic propagating in, and of ultrasonic interaction with, biological media.

JULIUS J. HARWOOD, 95, retired director, Materials Science Laboratory, Ford Motor Company, died on September 4, 2014. Mr. Harwood was elected to the NAE in 1977 for leadership and organization of research programs in industry and government.

R. RICHARD HEPPE, 91, retired president, Lockheed California Co., died on January 18, 2015. Mr Heppe was elected to the NAE in 1982 for continued significant contributions to the aerodynamics, design, and disciplined technical management of numerous military and commercial aircraft developments.

DAVID G. HOAG, 89, retired senior fellow, the Charles Stark Draper Laboratory Inc., died on January 19, 2015. Mr. Hoag was elected to the NAE in 1979 for contributions and leadership in development of guidance and control systems for the Polaris missile and the Apollo spacecrafts.

CHARLES V. JAKOWATZ, JR., 63, retired manager, Signal Processing and Research Department, Sandia National Laboratories, died on February 7, 2015. Dr. Jakowatz was elected to the NAE in 2003 for innovations in synthetic-aperture radar-image processing critical to military applications and environmental monitoring.

EDWARD J. KRAMER, 75, professor of materials and chemical engineering, University of California, Santa Barbara, died on December 27, 2014. Dr. Kramer was elected to the NAE in 1989 for pioneering investigations of the fundamental aspects of fracture and diffusion in polymers.

STEPHEN H. MASLEN, 89, retired associate director, Martin Marietta Laboratories, Martin Marietta Technologies Inc., died on March 24, 2015. Dr. Maslen was elected to the NAE in 1987 for major contributions to the application of fluid mechanics to the solution of numerous important problems in aerospace, nuclear, and industrial engineering.

WALTER G. MAY, 96, professor emeritus, University of Illinois at Urbana-Champaign, died on February 18, 2015. Dr. May was elected to the NAE in 1978 for contributions to engineering theory and practice in the fields of fluidization, high-energy propellants, LNG technology, and centrifugal isotope separation.

DANE A. MILLER, 69, cofounder, Biomet Inc., died February 10, 2015. Dr. Miller was elected to the NAE in 2000 for outstanding contributions to the orthopedic implant industry, for successfully creating a multinational corporation, and for unparalleled leadership in the biomedical engineering community.

ROBERT E. NICKELL, 79, president, Applied Science & Technology, died on January 21, 2015. Dr. Nickell was elected to the NAE in 2007 for contributions to the finite element method and the safe operation of power plants.

YIH-HSING PAO, 83, professor, Zhejiang University, died on June 18, 2013. Dr. Pao was elected to the NAE in 1985 for contributions of basic significance and for stimulating innovative applications in the field of wave propagation in elastic solids.

EUGENE M. RASMUSSON, 86, research professor emeritus, University of Maryland, College Park, died on March 22, 2015. Dr. Rasmusson was elected to the NAE in 1999 for contributions to understanding climate variability and establishing the basis for practical predictions of El Niño.

ERIC H. REICHL, 100, retired president, Conoco Coal Development Company, died on November 13, 2014. Mr. Reichl was elected to the NAE in 1975 for contributions and technical leadership in research and engineering on coal technology.

RAYMOND E. SMALLMAN, 85, professor emeritus, University of Birmingham, died on February 25, 2015. Dr. Smallman was elected to the NAE as a foreign member in 2005 for fundamental studies of defects in solids produced by irradiation damage and plastic deformation.

GUNNAR H. SOHLENIUS, 79, professor emeritus, KTH-Royal Institute of Technology, died on January 2, 2015. Dr. Sohlenius was elected to the NAE as a foreign member in 1991 for pioneering contributions to robotics and computer-integrated manufacturing in both industry and academe.

JOEL S. SPIRA, 88, chair, founder, and director of research, Lutron Electronics Company Inc., died on April 8, 2015. Mr. Spira was elected to the NAE in 1994 for integrating semiconductor technology to lighting products, creating an internationally competitive company, and for continuing work with engineering education.

PAUL E. TORGERSEN, 83, president emeritus, Virginia Polytechnic Institute and State University, died on March 29, 2015. Dr. Torgersen was elected to the NAE in 1986 for developments in simulation and gaming concepts, and for leadership in industrial engineering and engineering education.

CHARLES HARD TOWNES, 99, professor emeritus of physics, University of California, Berkeley, died on January 27, 2015. Dr. Townes was elected to the NAE in 1998 for the development of the maser and laser.

Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Research Council (NRC). Unless otherwise noted, all publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street NW–Keck 360, Washington, DC 20001. For more information or to place an order, contact NAP online at <*www.nap.edu*> or by phone at (800) 624-6242. *(Note: Prices quoted are subject to change without notice. There is a 10 percent discount for online orders when you sign up for a MyNAP account. Add $6.50 for shipping and handling for the first book and $1.50 for each additional book. Add applicable sales tax or GST if you live in CA, CT, DC, FL, MD, NC, NY, PA, VA, WI, or Canada.)*

Making Value for America: Embracing the Future of Manufacturing, Technology, and Work. Globalization, developments in technology, and new business models are transforming the way products and services are conceived, designed, made, and distributed in the United States and around the world. These forces present challenges—lower wages and fewer jobs for a growing fraction of middle-class workers—as well as opportunities for "makers" and entrepreneurs to create new types of businesses and jobs. This report examines these challenges and opportunities and offers recommendations for collaborative actions between government, industry, and education institutions to help ensure that the United States thrives amid global economic changes and remains a leading environment for innovation. The report illustrates the need for widespread adoption of best practices, a well-prepared and innovative workforce, local innovation networks to support startups and new products, improved flow of capital investments, and infrastructure upgrades.

NAE members on the study committee were **Nicholas M. Donofrio** (chair), NMD Consulting LLC, and IBM fellow emeritus and retired executive vice president, Innovation and Technology, IBM Corporation; **Lawrence D. Burns**, professor of engineering practice, University of Michigan, and retired vice president, R&D and Strategic Planning, General Motors Corporation; **Dean Kamen**, president, DEKA Research and Development Corporation; **Linda P.B. Katehi**, chancellor, University of California, Davis; **Ann L. Lee**, senior vice president, Genentech Inc., and head, Global Technical Development, Roche; **Arunava Majumdar**, Jay Precourt Professor and senior fellow, Precourt Institute for Energy, Department of Mechanical Engineering, Stanford University; **Jonathan J. Rubinstein**, former executive chair and CEO, Palm Inc.; and **John J. Tracy**, chief technology officer and senior vice president, Engineering, Operations and Technology, The Boeing Company. Paper, $46.00.

The Past Half Century of Engineering—And a Look Forward: Summary of a Forum. Engineering is poised to make an even greater contribution to society in the next half century than it has made in the past half century. At its annual meeting in September 2014 the NAE celebrated the 50th anniversary of its founding. A highlight of the meeting was a forum of distinguished speakers who considered the achievements of the last 50 years and looked toward the potential achievements of the next 50. This report summarizes their presentations.

The NAE members who spoke at the forum were **Wanda M. Austin**, president and chief executive officer, the Aerospace Corporation; **Corale L. Brierley**, principal, Brierley Consultancy LLC; **Leonard Kleinrock**, Distinguished Professor, Computer Science Department, University of California, Los Angeles; **Robert W. Lucky**, retired corporate vice president, Applied Research, Telcordia Technologies; **Arunava Majumdar**, Jay Precourt Professor and senior fellow, Precourt Institute for Energy, Department of Mechanical Engineering, Stanford University; **Roderic I. Pettigrew**, director, National Institute of Biomedical Imaging and Bioengineering; and **Robert E. Schafrik**, retired general manager, Materials and Process Engineering Department, GE Aviation. Paper, $39.00.

Educate to Innovate: Factors That Influence Innovation—Based on Input from Innovators and Stakeholders. Robust innovation in the United States is key to a strong and competitive industry and workforce. How is the United States preparing its students and workers to innovate and excel? What skills and attributes need to be nurtured? The aim of this project is to expand and improve the innovative capacity of individuals and organizations by identifying critical skills, attributes, and best practices—indeed, cultures—for nurturing them. This report summarizes the keynote and plenary presentations from an October 2013 workshop that brought together innovators and leaders from various fields to share insights on innovation and its education. It describes the specific skills, experiences, and environments that contribute to the success of innovators, and suggests next steps based on the workshop discussions.

NAE members on the project advisory committee were **Arden L. Bement, Jr.**, David A. Ross Distinguished Professor of Nuclear Engineering Emeritus and director, Global Policy Research Institute and Global Affairs Officer, Purdue University; **Jared L. Cohon**, president emeritus and University Professor, Department of Civil and Environmental Engineering, Carnegie Mellon University; **Nicholas M. Donofrio**, NMD Consulting LLC, and IBM fellow emeritus and retired executive vice president, Innovation and Technology, IBM Corporation; **James J. Duderstadt**, president emeritus and University Professor of Science and Engineering, University of Michigan; and **C. D. Mote, Jr.**, president, National Academy of Engineering, and vice chair, National Research Council. Paper, $40.00.

The Flexible Electronics Opportunity. Flexible electronics describes circuits that can bend and stretch, enabling significant versatility in applications, the prospect of low-cost manufacturing processes, and advantages in terms of their performance characteristics and potential range of applications, ranging from medical care, packaging, lighting and signage, consumer electronics and alternative energy (especially solar energy). They depend on efficient manufacturing that currently requires improved technology, processes, tooling, and materials as well as research. This report reviews the goals, structure, operation, and funding levels of foreign programs similar to major US programs (e.g., innovation awards, S&T parks, and consortia) and their potential to advance flexible electronics technology in the United States. The report recommends collaboration among industry, universities, and government to achieve both the critical levels of investment and the acceleration of new technology development that are needed to catalyze a vibrant flexible electronics industry.

NAE members on the study committee were **Stephen R. Forrest**, professor, Departments of EECS, Physics, and Materials Science & Engineering, University of Michigan, and **Mary L. Good**, dean emerita, special advisor to the chancellor for economic development, University of Arkansas at Little Rock, and former under secretary for technology, US Department of Commerce. Paper, $65.00.

Ranking Vaccines: Applications of a Prioritization Software Tool, Phase III—Use Case Studies and Data Framework. SMART Vaccines—Strategic Multi-Attribute Ranking Tool for Vaccines—is a prioritization software tool developed by the Institute of Medicine that utilizes decision science and modeling to help inform choices among candidates for new vaccine development. A blueprint for this computer-based guide was presented in a 2012 report (Phase I) and refined in the 2013 Phase II report. This report demonstrates practical applications of the tool through use case scenarios in partnership with the Public Health Agency of Canada, New York State Department of Health, and Serum Institute of India. The report also explores a novel application for determining new vaccine product profiles and offers practical strategies for data synthesis and estimation to encourage the broader use of the software.

NAE members on the study committee were **Paul Citron**, retired vice president, Technology Policy and Academic Relations, Medtronic Inc., and **Guy Lewis Steele, Jr.**, Software Architect, Oracle Labs. Paper, $75.00.

Robust Methods for the Analysis of Images and Videos for Fisheries Stock Assessment: Summary of a Workshop. The National Marine Fisheries Service (NMFS) is responsible for the stewardship of the nation's living marine resources and their habitat. As part of this charge, NMFS conducts assessments of the abundance and composition of fish stocks, relying heavily on human data gathering and analysis. Automatic methods of fish stock assessments can improve efficiency, reduce human workload, and perhaps produce higher-fidelity measurements; indeed, images and video, together with appropriate statistical analyses of the inferred data, are increasingly used. This report is the summary of a workshop convened by the NRC Committee on Applied and Theoretical Statistics to discuss analysis techniques for images and videos for fisheries stock assessment. Experts from diverse communities shared perspectives about the most efficient path toward improved automation of visual information and discussed near- and long-term goals that can be achieved through research and development.

NAE member **Ruzena K. Bajcsy**, NEC Chair Professor of EECS and director emerita of CITRIS, EECS Department, University of California, Berkeley, was a member of the workshop planning committee. Paper, $46.00.

Opportunities for the Employment of Simulation in US Air Force Training Environments: A Workshop Report. Simulators currently provide an alternative to aircraft for military and commercial training. For the US Air Force, in particular, simulation for training offers a cost-effective and often safer way (in comparison with live flying) to replicate real-world missions. But technical issues such as simulation fidelity and multilevel security, among others, need to be addressed if the Air Force is to take full advantage of this technology. A November 2014 workshop examined the status of simulation training, alternative uses, current and future technologies, and how the combination of simulation and live training can improve aircrew training.

NAE member **Donald C. Fraser**, retired, Draper Laboratory, cochaired the workshop committee. Paper, $39.00.

A Review of the US Navy Cyber Defense Capabilities: Abbreviated Version of a Classified Report. At the request of the Chief of Naval Operations, an NRC-appointed expert committee reviewed the US Navy's cyber defense capabilities. The Department of the Navy determined that the committee's report was classified in its entirety under Executive Order

13526 and therefore cannot be made available to the public. This abbreviated unclassified report provides background information on the full report and the authoring committee.

NAE members on the committee were **Barry M. Horowitz**, professor of systems engineering, University of Virginia; **Arthur L. Money**, former assistant secretary of defense, US Department of Defense; and **Fred B. Schneider**, Samuel B. Eckert Professor of Computer Science, Cornell University. Free PDF.

Reliability Growth: Enhancing Defense System Reliability. The failure of a high percentage of defense systems to meet their reliability requirements is a serious problem for the US Department of Defense and the nation: the systems not only are less likely to successfully carry out their intended missions but also could endanger the operators' lives. Furthermore, reliability failures discovered after deployment can result in costly and strategic delays and the need for expensive redesign, often limiting the tactical situations in which the system can be used. Finally, systems that fail to meet their reliability requirements are much more likely to need additional scheduled and unscheduled maintenance and to need more spare parts and possibly replacement systems, all of which can substantially increase lifecycle costs. In 2008 DOD undertook a concerted effort to raise the priority of reliability through greater use of design for reliability techniques, reliability growth testing, and formal reliability growth modeling, by contractors and DOD units alike. Handbooks, guidances, and formal memoranda were revised or newly issued to reduce the frequency and effects of reliability deficiencies for defense systems in operational testing. This report evaluates these changes and assesses how current DOD principles and practices could be modified to increase the likelihood that defense systems will satisfy their reliability requirements. In addition, the report defines modern design and testing for reliability, discusses the contractor's role in reliability testing, and summarizes the current state of formal reliability growth modeling.

NAE member **W. Peter Cherry**, independent consultant, Ann Arbor, Michigan, was a member of the study panel. Paper, $60.00.

Aligning the Governance Structure of the NNSA Laboratories to Meet 21st Century National Security Challenges. This report is an independent assessment of the transition of the National Nuclear Security Administration (NNSA) laboratories (Los Alamos, Lawrence Livermore, and Sandia) to multiagency, federally funded research and development centers (FFDRCs) with direct sustainment and sponsorship by multiple national security agencies. According to this report, the Department of Energy should remain the sole sponsor of the NNSA laboratories as FFDRCs, but the report makes recommendations for the governance of NNSA laboratories to better align with the evolving national security landscape and the laboratories' increasing engagement with the other national security agencies, while simultaneously encouraging the best technical solutions to national problems from the entire range of national security establishments.

NAE members on the study committee were **Richard A. Meserve** (chair), president emeritus, Carnegie Institution for Science; **Arden L. Bement, Jr.**, David A. Ross Distinguished Professor of Nuclear Engineering Emeritus, director, Global Policy Research Institute and Global Affairs Officer, Purdue University; **Warren F. (Pete) Miller, Jr.**, TEES Distinguished Research Professor, Department of Nuclear Engineering, Texas A&M University System, and former assistant secretary for nuclear energy, US Department of Energy, and Los Alamos National Laboratory (retired); and **James M. Tien**, Distinguished Professor and dean, College of Engineering, University of Miami. Paper, $40.00.

Developing a Framework for Measuring Community Resilience: Summary of a Workshop. The 2012 NRC report *Disaster Resilience: A National Imperative* found that "without numerical means of assessing resilience, it would be impossible to identify the priority needs for improvement, to monitor changes, to show that resilience had improved, or to compare the benefits of increasing resilience with the associated costs." Metrics and indicators to evaluate progress, and the data necessary to establish them, are critical, both to help communities clarify and formalize what the concept of resilience means for them and to support efforts to develop and prioritize resilience investments. The 2012 report called for government entities at federal, state, and local levels and professional organizations to develop a framework for communities to adapt to their circumstances and begin to track their progress toward increasing resilience. To that end, the National Academies' Resilient America Roundtable held a workshop on Measures of Community Resilience: From Lessons Learned to

Lessons Applied in September 2014 to begin to develop a framework of measures and indicators that could support community efforts to increase their resilience. The framework will be further developed through feedback and testing in pilot and other partner communities working with the roundtable. This report is a summary of the one-day workshop.

NAE member **Gerald E. Galloway, Jr.**, Glenn L. Martin Institute Professor of Engineering, University of Maryland, College Park, was a member of the workshop steering committee. Paper, $42.00.

Review Criteria for Successful Treatment of Hydrolysate at the Pueblo Chemical Agent Destruction Pilot Plant. One of the last two US sites with chemical munitions and chemical materiel is the Pueblo Chemical Depot in Colorado, where the stockpile consists of about 800,000 projectiles and mortars, all of them filled with the chemical agent mustard. Under the direction of the Assembled Chemical Weapons Alternative Program (ACWA), the Army has constructed the Pueblo Chemical Agent Destruction Pilot Plant (PCAPP) to destroy these munitions. The primary technology to be used is hydrolysis, which will result in a secondary waste stream called hydrolysate. Because the technologies involved have never been combined to treat mustard hydrolysate, the US Army asked that an NRC committee review the criteria for successfully treating the hydrolysate. This report provides information on the composition of the hydrolysate, describes the PCAPP processes for treating it, establishes criteria for successful treatment, and identifies systemization data that should factor into the criteria and decision process for transport and disposal at a permitted hazardous waste disposal facility. It also discusses stakeholder concerns; regulatory considerations at the federal, state, and local levels; Department of Transportation regulations and risks associated with off-site shipment of the hydrolysate; and failure risks and contingency options as well as the downstream impacts of a decision to ship hydrolysate offsite.

NAE member **Philip C. Singer**, professor emeritus, University of North Carolina at Chapel Hill, was a member of the study committee. Paper, $45.00.

Bulk Collection of Signals Intelligence: Technical Options. Presidential Policy Directive 28 (PPD-28), issued in January 2014, instructed the Office of the Director of National Intelligence (ODNI) to produce a report within one year "assessing the feasibility of creating software that would allow the intelligence community more easily to conduct targeted information acquisition rather than bulk collection." ODNI asked the NRC to conduct a study, begun in June 2014, to assist in its response to the president. The study committee concluded that, although no software can fully replace bulk with targeted information collection, software can be developed to more effectively target collection and to control the usage of collected data; automatic controls on the usage of data collected in bulk can help to enforce privacy protections; and research and development can help in developing software intended to (1) enhance the effectiveness of targeted collection and (2) improve automated usage controls.

NAE members on the study committee were **Robert F. Sproull** (chair), adjunct professor of computer science, University of Massachusetts, Amherst, and retired vice president and director, Oracle Labs, and **Butler W. Lampson**, technical fellow, Microsoft Corporation. Paper, $44.00.

2013–2014 Assessment of the Army Research Laboratory. The NRC Army Research Laboratory Technical Assessment Board (ARLTAB) provides biennial assessments of the scientific and technical quality of the research, development, and analysis programs at the Army Research Laboratory, focusing on ballistics sciences, human sciences, information sciences, materials sciences, and mechanical sciences. This report, a summary of the board's findings for the first biennial assessment, discusses the assessment process used by the board and its five panels; provides detailed assessments of each of the ARL core technical competency areas reviewed during the 2013–2014 period; and presents findings and recommendations common across multiple competency areas.

NAE members on the assessment board were **Jennie S. Hwang** (chair from 2/6/14), CEO, H-Technologies Group and board trustee, and Distinguished Adjunct Professor, Case Western Reserve University; **R. Byron Pipes** (chair until 2/5/14), John L. Bray Distinguished Professor of Engineering, Purdue University; and **Wesley L. Harris**, Charles Stark Draper Professor of Aeronautics and Astronautics and associate provost, Massachusetts Institute of Technology. Paper, $49.00.

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