Tackling Climate Change in the U.S.

Potential Carbon Emissions Reductions from Energy Efficiency and Renewable Energy by 2030

American Solar Energy Society
Charles F. Kutscher, Editor
January 2007

Front cover: A stream of melt water cascades off the vast Arctic ice sheet
that covers Greenland. Scientists attribute acceleration
in the melting of ice sheets to global warming.
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Foreword

Climate change is happening. Animals know it. Many are beginning to migrate to stay within their climate zones. But some are beginning to run out of real estate. They are in danger of being pushed off the planet, to extinction.

Even humans are starting to notice climate change. And they are learning that unabated climate change poses great dangers, including rising sea levels and increased regional climate extremes. Yet the public is not fully aware of some basic scientific facts that define an urgency for action. One stark implication—we must begin fundamental changes in our energy use now, phasing in new technologies over the next few decades, in order to avoid human-made climate disasters.

Indeed, a quarter of the carbon dioxide (CO_2) that we put in the air by burning fossil fuels will stay there “forever”—more than 500 years. This makes it imperative to develop technologies that reduce emissions of CO_2 to the atmosphere.

At first glance, the task is staggering. If we are to keep global temperatures from exceeding the warmest periods in the past million years—so we can avoid creating “a different planet”—we will need to keep atmospheric CO_2 to a level of about 450 parts per million (ppm). Already humans have caused CO_2 to increase from 280 to 380 ppm.

The limit on CO_2 must be refined, and we may find that it can be somewhat larger if we reduce atmospheric amounts of non-CO_2 pollutants, such as methane, black soot, and carbon monoxide. There are other good reasons to reduce those pollutants, so it is important to address them. However, such efforts will only moderately reduce the magnitude of the task of reducing CO_2 emissions.

When I spoke at the SOLAR 2006 conference in Denver last summer, I was pleased to see the progress being made by experts in energy efficiency and renewable energies. This report contains a special series of nine papers from that conference. The papers show the great potential to reduce carbon emissions via energy efficiency, concentrating solar power, photovoltaics, wind energy, biomass, biofuels, and geothermal energy.

Clearly these technologies have the potential to meet the requirements to reduce our nation’s emissions, consistent with the need to reduce global emissions. No doubt the cost and performance of these technologies can benefit from further research and development, but they are ready now to begin to address the carbon problem. To bolster our economy and provide good, high-tech, high-pay jobs, it is important that we move ahead promptly, so that we can be a world leader in these developing technologies.

Some climate change is already underway, but there is still time to avoid disastrous climate change. The benefits of making reductions in carbon emissions our top national priority would be widespread, especially for our energy independence and national security.

Most people want to exercise responsible stewardship with the planet, but individual actions, in the absence of standards and policies, cannot solve the problem. In my personal opinion, it is time for the public to demand effective leadership from Washington in these energy and climate matters. We owe that to our children and grandchildren, so that they can enjoy the full wonders of creation.

James E. Hansen, Ph.D.
Director, Goddard Institute for Space Studies*
January 2007
New York City

*Affiliation for identification purposes only. Opinions regarding climate change and policy implications are those of the author, and are not meant to represent a government position.

Acknowledgements

For more than fifty years, the American Solar Energy Society (ASES) has led the nation in disseminating information about the full range of renewable energy technologies. We are pleased to offer ***Tackling Climate Change in the U.S.: Potential Carbon Emissions Reductions from Energy Efficiency and Renewable Energy by 2030***. This is an important and timely contribution to ASES's ongoing work to accelerate the U.S. transition to a sustainable energy economy.

This report is the culmination of an effort that began during the planning of the 35th Annual National Solar Energy Conference, SOLAR 2006. The project was the brainchild of Chuck Kutscher, the SOLAR 2006 conference chair. He invited experts to calculate the potential for accelerating the deployment of mature renewable energy technologies and to present their findings at SOLAR 2006. Similarly, Dr. Kutscher recruited experts to report on the potential carbon emission reductions from aggressive energy efficiency measures in industrial processes, transportation, and the built environment.

After the conference, ASES subjected the experts' papers to a rigorous review process, Dr. Kutscher wrote an overview and summary, and this report is the final result. The six renewable energy technologies presented at the conference and in this report include concentrating solar power, photovoltaics, wind power, biomass, biofuels, and geothermal power.

We acknowledge and publicly thank Chuck Kutscher for his leadership of SOLAR 2006 and this study. We acknowledge the technical authors and presenters of the nine special track papers: Joel Swisher, Marilyn Brown, Therese Stovall, Patrick Hughes, Peter Lilienthal, Howard Brown, Mark Mehos, Dave Kearney, Paul Denholm, Robert Margolis, Ken Zweibel, Michael Milligan, Ralph Overend, Anelia Milbrandt, John Sheehan, Martin Vorum, and Jeff Tester. We thank the climate scientists who joined us at SOLAR 2006 and presented their most recent data demonstrating the urgent need to act to reduce greenhouse gas emissions: James Hansen, Warren Washington, Robert Socolow, and Marty Hoffert.

Finally, we thank the funders who made this report and its distribution possible: Stone Gossard and Pearl Jam's Carbon Portfolio Strategy, the U.S. Environmental Protection Agency, John Reynolds, and Glen Friedman, along with the hundreds of ASES members whose contributions support this and other worthy projects.

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ASES is solely responsible for the content of this report and encourages its broad distribution to help stimulate debate on reducing our national carbon footprint.

Brad Collins
ASES Executive Director
January 2007
Boulder, Colorado

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Tackling Climate Change in the U.S.

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Executive Summary

Charles F. Kutscher, Ph.D., P.E.
American Solar Energy Society

Energy efficiency and renewable energy technologies have the potential to provide most, if not all, of the U.S. carbon emissions reductions that will be needed to help limit the atmospheric concentration of carbon dioxide to 450 to 500 ppm.

Photo Courtesy: NASA

For SOLAR 2006, its 35th Annual National Solar Energy Conference last July, the American Solar Energy Society (ASES) chose to address global warming, the most pressing challenge of our time. Under the theme "Renewable Energy: Key to Climate Recovery," climate experts James Hansen of the National Aeronautics and Space Administration (NASA), Warren Washington of the National Center for Atmospheric Research (NCAR), Robert Socolow of Princeton University, and Marty Hoffert of New York University (NYU) described the magnitude of the global warming crisis and what is needed to address it.

A key feature of the conference was a special track of nine invited presentations by experts in energy efficiency and renewable energy that detailed the potential for these technologies—in an aggressive but achievable climate-driven scenario—to address the needed U.S. carbon emissions reductions by the years 2015 and 2030. These presentations covered energy efficiency in buildings, industry, and transportation, as well as the following renewable technologies: concentrating solar power, photovoltaics, wind, biomass, biofuels, and geothermal. Since the conference, these studies were subjected to additional review and were revised for publication in this special ASES report.

According to Hansen, NASA's top climate scientist, we need to limit the additional average world temperature rise due to greenhouse gases to 1°C above the year-2000 level. If we fail, we risk entering an unprecedented warming era that would have disastrous consequences, including rising sea levels and large-scale extinction of species. Limiting temperature rise means limiting the carbon dioxide (CO_2) level in the atmosphere to 450 to 500 parts per million (ppm).

What does this mean for the United States? Estimates are that industrialized nations must reduce emissions about 60% to 80% below today's values by mid-century. Figure 1 shows the U.S. reductions that would be needed by 2030 to be on the right path. Accounting for expected economic growth and associated increases in carbon emissions in a business-as-usual (BAU) case, in 2030 we must be displacing between 1,100 and 1,300 million metric tons of carbon per year (MtC/yr).

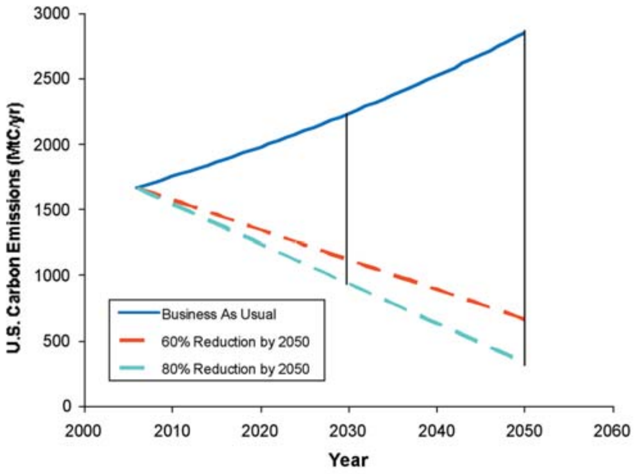


Figure 1. Triangle of U.S. fossil fuel carbon reductions needed by 2030 for a 60% to 80% reduction from today's levels by 2050.

The SOLAR 2006 exercise looked at energy efficiency and renewable energy technologies to determine the potential carbon reduction for each. The authors of the renewable technology papers were asked to describe the resource, discuss current and expected future costs, and develop supply and carbon-reduction curves for the years 2015 and 2030.

Table 1 summarizes the potential carbon-reduction contributions from the various areas. (Energy efficiency contributions in the buildings, transportation, and industry sectors are combined into one number.) Figure 2 shows all the contributions on one graph. Approximately 57% of the total carbon-reduction contribution is from energy efficiency (EE) and about 43% is from renewables. Energy efficiency measures can allow U.S. carbon emissions to remain about level through 2030, whereas the renewable supply technologies can provide large reductions in carbon emissions below current values.

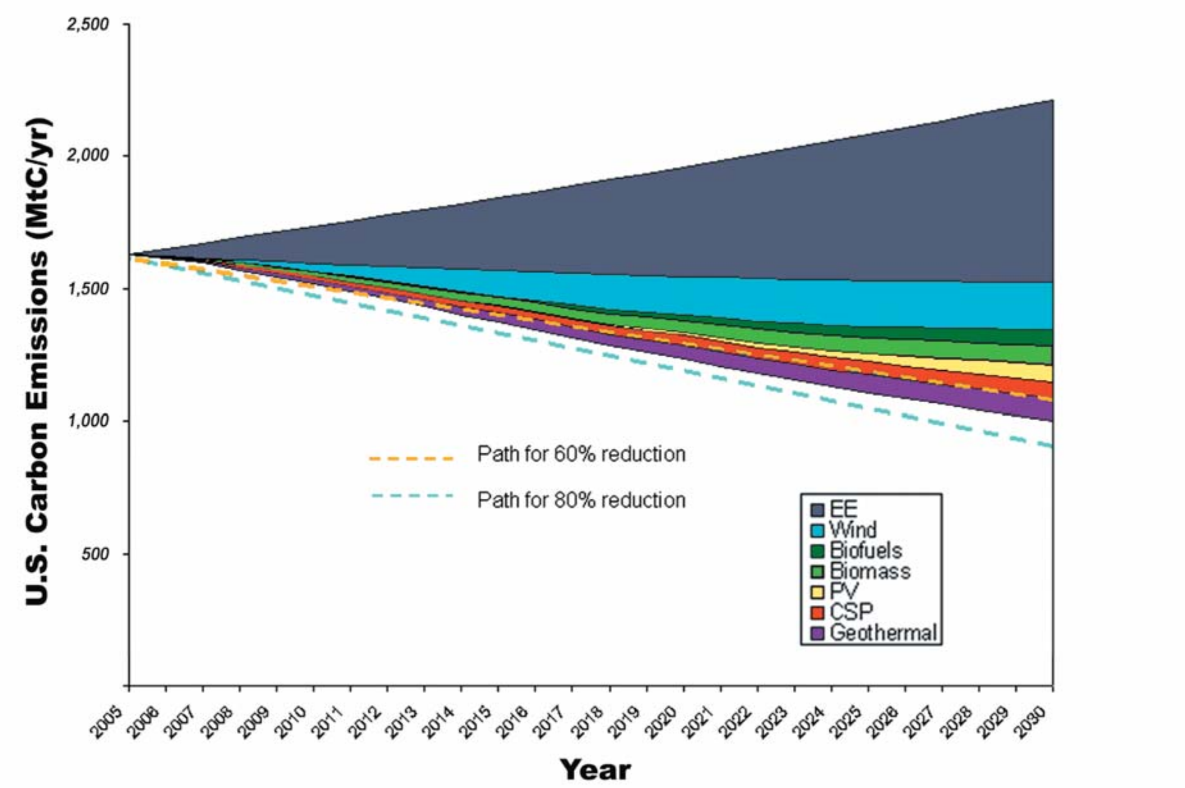


Figure 2. Potential carbon reductions in 2030 from energy efficiency and renewable technologies and paths to achieve reductions of 60% and 80% below today's emissions value by 2050.

Table 1.
Potential carbon reductions (in MtC/yr in 2030) based on the middle of the range of carbon conversions.

Energy efficiency	688
Concentrating solar power	63
Photovoltaics	63
Wind	181
Biofuels	58
Biomass	75
Geothermal	83

The U.S. is extremely rich in renewable energy resources. Figure 3 shows how the various potential renewable contributions in 2030 are distributed throughout the country.

The carbon-reduction potentials for the year 2030 total between 1,000 and 1,400 MtC/yr, or an average of about 1,200 MtC/yr based on a mid-range value for electricity-to-carbon conversion. This would put the U.S. on target to achieve the necessary carbon-emissions reductions by mid-century. A national commitment that includes effective policy measures and continued research and development will be needed to realize these potentials. Integration of these technologies in the marketplace could reduce these potentials somewhat due to competition and overlap in some U.S. regions. On the other hand, even greater wind and solar contributions might be possible through greater use of storage and high-efficiency transmission lines.

The studies focused on the use of renewable energy in the electricity and transportation sectors, as these together are responsible for nearly three-quarters of U.S. carbon emissions from fossil fuels. Goals for renewables are often stated in terms of a percentage of national energy.

The results of these studies show that renewable energy has the potential to provide approximately 40% of the U.S. electric energy need projected for 2030 by the Energy Information Administration (EIA). After we reduce the EIA electricity projection by taking advantage of energy efficiency measures, renewables could provide about 50% of the remaining 2030 U.S. electric need.

There are uncertainties associated with the values estimated in the papers, and, because these were primarily individual technology studies, there is uncertainty associated with combining them. The results strongly suggest, however, that energy efficiency and renewable energy technologies have the potential to provide most, if not all, of the U.S. carbon emissions reductions that will be needed to help limit the atmospheric concentration of carbon dioxide to 450 to 500 ppm.

We hope this work will convince policymakers to seriously consider the contributions of energy efficiency and renewable technologies for addressing global warming. Because global warming is an environmental crisis of enormous magnitude, we cannot afford to wait any longer to drastically reduce carbon emissions. Energy efficiency and renewable technologies can begin to be deployed on a large scale today to tackle this critical challenge.

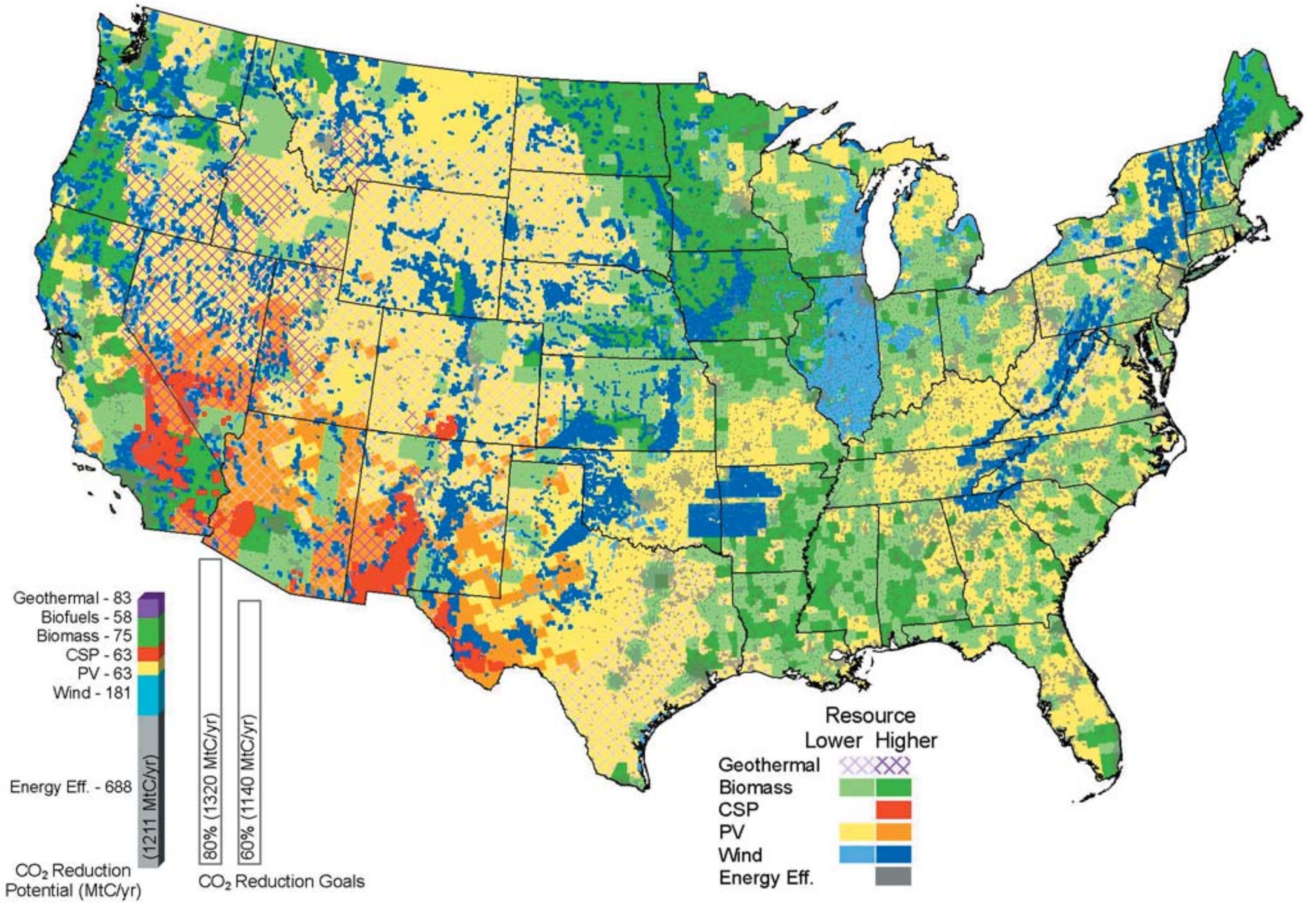


Figure 3. U.S. map indicating the potential contributions from energy efficiency and renewable energy by 2030. CSP and wind are based on deployment scenarios; other renewables indicate resource locations.

Tackling Climate Change in the U.S.

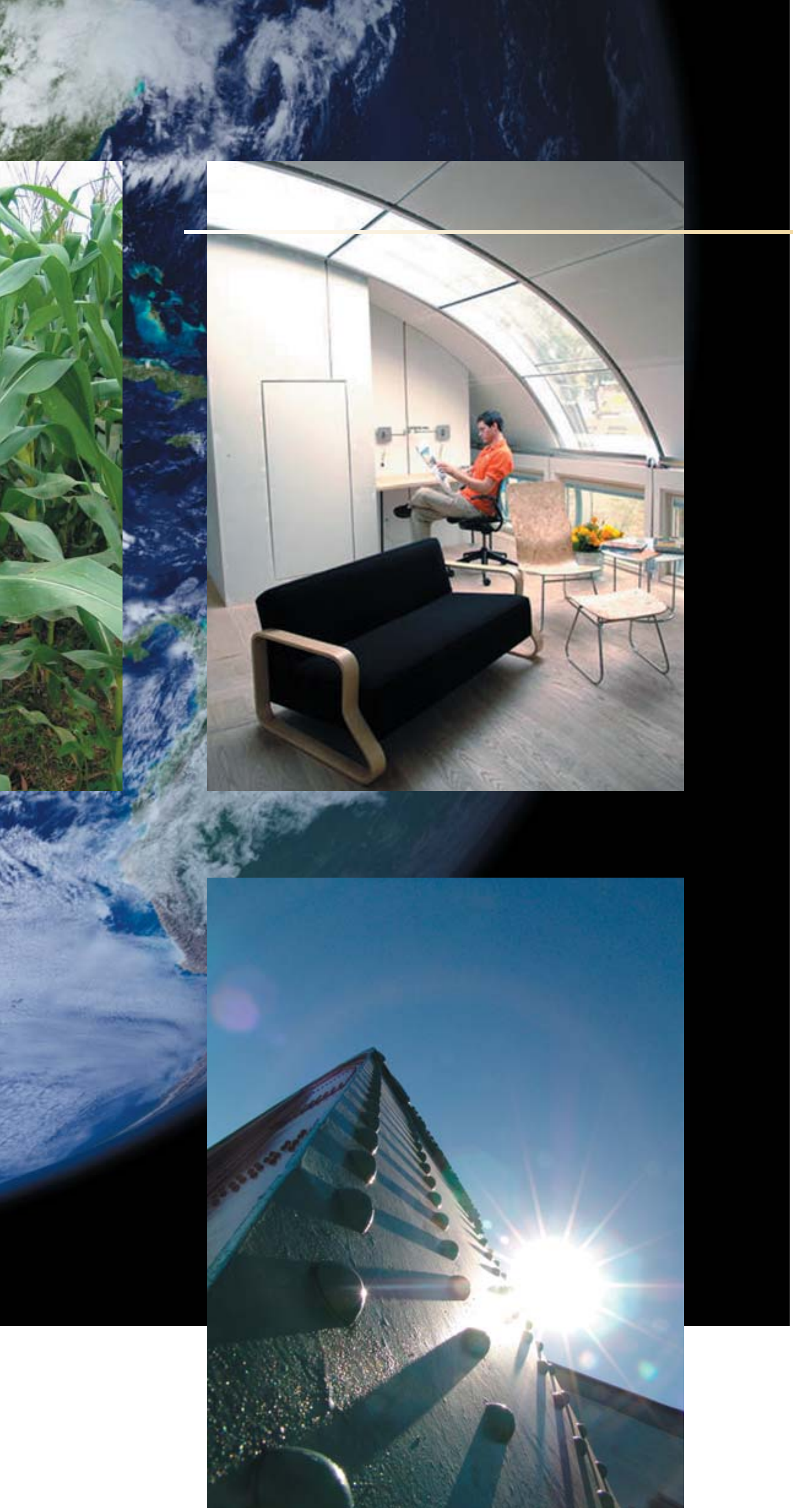
Potential Carbon Emissions Reductions from Energy Efficiency and Renewable Energy by 2030

Overview and Summary of the Studies

Charles F. Kutscher, Ph.D., P.E.
American Solar Energy Society

Earth photo this page and section covers: NASA
Smaller photos clockwise from left: Chuck Kutscher;Cielo Wind Power/NREL; Sanjay Pindiyath/morguefile.com; Chris Gunn/NREL; Michelle Kwajafa

Energy efficiency and renewable energy technologies are available today for large-scale deployment to immediately begin reducing carbon emissions.



Introduction

The SOLAR 2006 national solar conference held in Denver from July 8 through 13, 2006, had as its theme, “Renewable Energy: Key to Climate Recovery.” Experts in climate change, including Dr. James Hansen of the National Aeronautics and Space Administration (NASA), Dr. Warren Washington of the National Center for Atmospheric Research (NCAR), and Dr. Robert Socolow of Princeton University, described the key issues associated with global warming. Their presentations showed that the problem of global warming is extremely serious, that the burning of fossil fuels is the primary cause, and that there is little time left to act to prevent the most catastrophic consequences. See Appendix for an overview of the climate change problem.

In addition to discussions of the climate change issue, SOLAR 2006 featured a special track of nine presentations that described how energy efficiency and renewable energy technologies could mitigate climate change. These studies were not funded and were accomplished on a volunteer basis, in most cases by expanding on existing work. The purpose of these presentations was not to make projections or predictions, but rather to estimate the potential carbon reductions possible with an aggressive deployment of renewable energy and energy efficiency technologies in the United States by the years 2015 and 2030.

We did not give the volunteer authors carbon reduction targets, but rather asked them to develop carbon-reduction potentials based on an aggressive carbon reduction scenario. However, we did give them a template to help provide some uniformity in the way they developed the results. Before we summarize these results, it is worthwhile to put the global warming issue in context.

Putting the Challenge in Context

According to Dr. James Hansen, the National Aeronautics and Space Administration's (NASA's) top climate scientist, we need to limit additional temperature rise due to greenhouse gases to 1°C above the year 2000 levels. Exceeding those levels could trigger unprecedented warming with potentially disastrous consequences, including a large rise in sea level and large-scale extinction of species. This means limiting the carbon dioxide level in the atmosphere to between 450 and 500 parts per million (ppm), provided we also reduce methane and other emissions.

In a paper published in Science, Stephen Pacala and Robert Socolow (2004) of Princeton University described a simplified scenario that would allow the carbon dioxide in the atmosphere to level out at 500 ppm. Their approach involves limiting world CO_2 emissions to the current value of 7 billion metric tons of carbon (GtC) per year for 50 years, followed by substantial reductions. This means that the world must displace about 175 GtC over the next 50 years. They divide this amount into 7 "wedges" of 25 GtC each. Each wedge represents a different approach, such as energy efficiency, solar energy, nuclear, etc. (See Figure 1.) This report refers to emissions in terms of tons of carbon. One ton of carbon is equivalent to about 3.7 tons of CO_2.

What does this mean for the United States? Industrialized countries are responsible for roughly one-half of world carbon emissions. Developing countries are trying to catch up with the standard of living in the industrialized countries and are rapidly expanding their economies. They believe they have a right to fuel their expansions with cheap coal and other fossil fuels, just as we did.

Some experts hope that if we begin a serious transition to carbon-free energy sources, we will be able to convince developing nations to do the same. But we can expect that even under the best of circumstances, these nations will continue for some time to increase their carbon emissions. To achieve the needed worldwide carbon reductions, analysts estimate that industrialized countries must reduce emissions by about 60% to 80% below today's values by 2050. (Even with such large reductions, per capita annual carbon emissions in the U.S. would still be at about twice the world average at mid-century, down from approximately five times the world average today.)

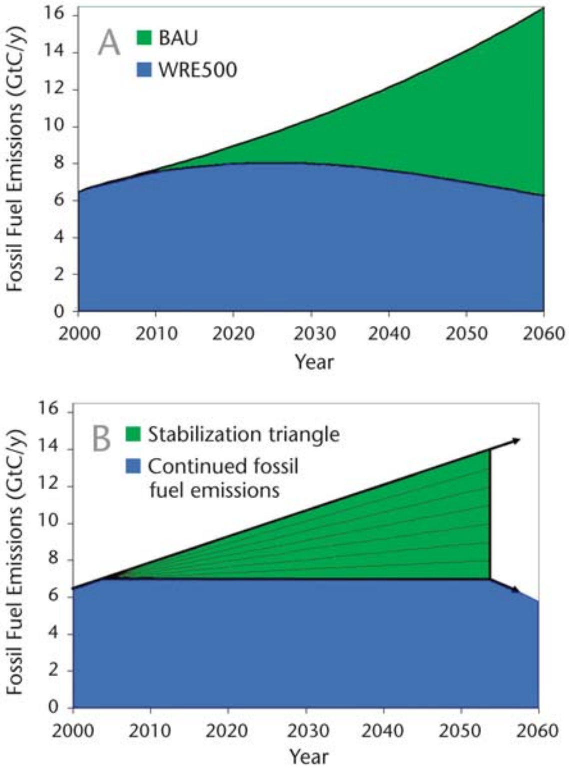


Figure 1. Illustration of A) the business-as-usual and carbon reduction curves and B) the idealized Pacala-Socolow "wedges" approach to describing needed world carbon emissions reductions. Carbon-free energy sources must fill the gap between business-as-usual (BAU) emissions growth and the path needed to stabilize atmospheric carbon at 450 to 500 ppm.

Figure 2 shows what reductions the United States would need to make by 2030 to be on target for carbon reductions of 60% to 80% below today's values by 2050 (the light blue and red lines respectively). This requires reductions of 33% to 44% below today's values by 2030, which corresponds to reductions from

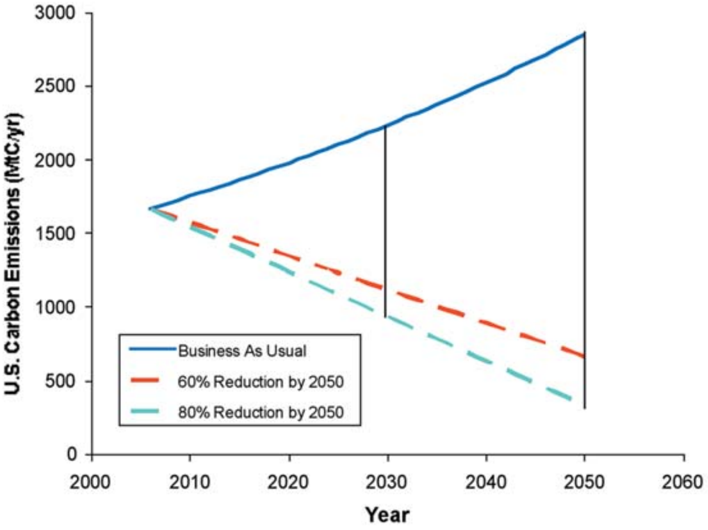


Figure 2. U.S. carbon reductions needed by 2030 for a 60% to 80% reduction from today's levels by 2050.

today's carbon emissions from fossil fuels of 1.6 GtC/yr to values of between 0.9 and 1.1 GtC/yr in 2030. Accounting for expected economic growth and associated increases in carbon emissions in a business-as-usual scenario (using information from the U.S. Department of Energy's [DOE's] Energy Information Administration [EIA]), this means that in 2030 we must be displacing between 1.1 and 1.3 GtC/yr (the difference between the dark blue line and the red and light blue lines at 2030).

Rather than arbitrarily dividing the gap between desired emissions and business-as-usual emissions into a number of equal-area wedges and determining how much of each technology would be needed to supply that wedge, as Pacala and Socolow did, the purpose of this exercise was to do more or less the opposite. We determined the potential size of the wedge for energy efficiency and for each renewable energy area to see how well the gap would be filled. Portions of the gap remaining unfilled can potentially be provided by nonrenewable low-carbon technologies, such as integrated gasification-combined cycle (IGCC) coal with carbon capture and sequestration, and nuclear power. (Of course, the combination of technologies, renewable and nonrenewable, that fill the gap will ultimately depend on cost, the effectiveness of carbon sequestration techniques, public desire, and policy measures.)

To achieve the needed worldwide carbon reductions, analysts estimate that industrialized countries must reduce emissions by about 60% to 80% below today's values by 2050.

Project Description

Analysts and modeling experts do most analyses of this type. We used a bottoms-up approach instead. That is, we asked experts in each technology to come up with their best estimates of what their technologies could do. However, they did obtain assistance from systems modeling and geographic information systems (GIS) experts as they prepared their studies. The technology experts recruited for this project were:

Overall Energy Efficiency
Joel Swisher (Rocky Mountain Institute)

Buildings
Marilyn Brown, Therese Stovall, and Patrick Hughes (Oak Ridge National Laboratory)

Plug-In Hybrid Electric Vehicles
Peter Lilienthal and Howard Brown (National Renewable Energy Laboratory [NREL])

Concentrating Solar Power (CSP)
Mark Mehos (NREL) and David Kearney (Kearney and Associates)

Photovoltaics (PV)
Paul Denholm and Robert Margolis (NREL) and Ken Zweibel (PrimeStar Solar, Inc.)

Wind Power
Michael Milligan (NREL)

Biomass
Ralph Overend and Anelia Milbrandt (NREL)

Biofuels
John Sheehan (NREL)

Geothermal Power
Martin Vorum (NREL) and Jefferson Tester (Massachusetts Institute of Technology [MIT])

We asked the authors of the renewable technology papers to cover resource availability, current and expected future costs, and energy supply and carbon reduction curves for the years 2015 and 2030. Donna Heimiller provided the authors with geographic information systems support. Nate Blair provided analytical support. A review panel reviewed the nine original papers. The authors presented the original papers at the SOLAR 2006 conference in a special three-day track from July 10 through 12, 2006. We presented a summary of the results at the conference closing luncheon.

Following the conference, the authors obtained additional technical reviews for their papers. Donald Aitken of the International Solar Energy Society (ISES) and Robert Lorand of Science Applications International Corporation (SAIC) also reviewed all the papers and this overview and summary. However, the contents of this report are the sole responsibilities of the authors. In addition, although many of the authors are National Renewable Energy Laboratory (NREL) employees, this report is a product of the American Solar Energy Society and not NREL.

The energy efficiency analysis covers efficiency in buildings, transportation, and industry and is based on work done by the Rocky Mountain Institute. The building energy paper, based on a report by Brown, et al., (2005) for the Pew Center on Climate Change, provides greater detail on what is possible in the important buildings sector. We included a paper on plug-in-hybrid electric vehicles because of the potential this technology has for reducing gasoline consumption as well as enabling intermittent renewables like wind by providing battery storage. The work on concentrating solar power (CSP) relies heavily on analysis done for the Western Governors' Association (WGA) Clean and Diversified Energy Study that focused on western states (where concentrating solar is being deployed). The authors estimated CSP's potential in a more aggressive climate-driven scenario. The authors covering wind and biomass also took results from the WGA study and extrapolated them across the United States, again with an aggressive climate-driven scenario in mind. The analysis of biofuels takes advantage of new analysis done for DOE.

Many of the studies involved displacing electric power generation. The amount of carbon reduced depends on the source of the electricity that is being displaced. A typical U.S. coal plant today emits about 260 metric tons of carbon per gigawatt-hour (GWh) of electricity produced. The average of the U.S. electric mix (which includes coal, natural gas, hydroelectric, nuclear, and some non-hydro renewables) is equivalent to 160 metric tons of carbon per GWh. Because coal is the worst offender in terms of carbon emissions, an aggressive carbon reduction scenario would focus on displacement of coal. However, this may not always be possible. To more accurately represent the likely carbon emissions, we thus report lower and upper values based on the two carbon conversions—the national average and current coal plants. Some carbon is emitted in constructing renewable electric power plants. However, estimates of life-cycle carbon emissions from renewable power generation technologies are on the order of only 1 to 2 metric tons of carbon per GWh and were neglected (Breeze, 2005).

The technology areas differ significantly and cannot necessarily be evaluated using the same techniques. In this summary, because we are trying to determine the total potential for these technologies to mitigate global warming, we considered the numbers on as even a playing field as possible. Although a more detailed, integrated study in the future can undoubtedly refine the numbers, it is critical that we begin deploying energy-efficiency and carbon-free renewable energy technologies as soon as possible, while simultaneously improving our analyses and continuing research and development (R&D) to lower costs. This report provides a new look at how energy efficiency and renewable energy can be applied to tackle the global warming challenge.

This report provides a new look at how energy efficiency and renewable energy can be applied to tackle the global warming challenge.

Summary of the Analyses

Energy Efficiency

Overall Energy Efficiency

Author Joel Swisher looked at total energy efficiency savings in the buildings, vehicles, and industry sectors. The buildings sector provided about 40% of the savings with the other two sectors providing about 30% each. Energy efficiency improvements in buildings result from better building envelope design, daylighting, more efficient artificial lighting, and better efficiency standards for building components and appliances. Improvements in transportation result from lighter-weight vehicles, public transit, improved aerodynamics, and more efficient propulsion systems. Energy reductions in industry accrue from heat recovery, more efficient motors and drives, and the use of cogeneration (also called combined heat and power or CHP) systems that provide both heat and electricity.

For efficiency savings in electricity, the study used results from the "five-lab study" (Scenarios of U.S. Carbon Reductions) done by the Interlaboratory Working Group on Energy-Efficient and Low-Carbon Technologies. Electricity savings resulted from efficiency improvements in the buildings and industry sectors. For estimates of efficiency savings associated with natural gas and petroleum, the author used analyses performed at the Rocky Mountain Institute. Natural gas savings accrued from more efficient industrial process heat and space and water heating in buildings. Oil savings came mostly from transportation improvements such as lighter-weight vehicles, improved aerodynamics, and better propulsion systems.

The study shows a reduction in electrical energy of 1,040 TWh in 2030. At the lower (national average) conversion of 160 metric tons of carbon per GWh, this provides a carbon savings of 166 million metric tons of carbon per year (MtC/yr). At the upper (coal) conversion of 260 metric tons of carbon per GWh, the carbon savings is 270 MtC/yr. The cost of saved electrical energy ranges from 0 to 4 cents per kilowatt-hour (kWh). Oil and gas savings are estimated to save 470 MtC/yr at costs of saved energy ranging from $0 to $5 per million Btu (MBtu). Thus the author estimates the total carbon savings to be between 636 and 740 MtC/yr, with an average of 688 MtC/yr.

The author combined the carbon savings from all sources to produce the carbon reduction curve in Figure 3, which shows the cost of saved energy in dollars per MBtu per year versus million metric tons of carbon per year. The curves include the high carbon and low carbon cases for electricity and the midrange values. Like supply curves that show the cost of electricity versus gigawatts (GW) deployed, this shows that to achieve higher and higher carbon reductions requires increasingly expensive options. However, all of these are at costs below $6/MBtu.

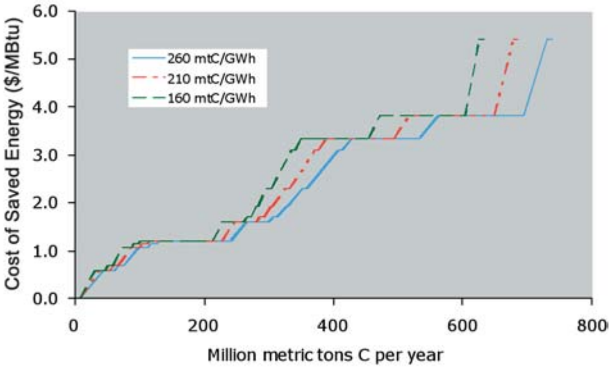


Figure 3. Cost of saved energy (in $/million Btu) versus carbon displacement (in millions of metric tons per year).

Buildings

Energy consumed in the buildings sector—including residential, commercial, and industrial buildings—is responsible for approximately 43% of U.S. carbon emissions. Building efficiency was included in the overall energy efficiency paper. However, because the buildings sector is such an important component of energy efficiency, Marilyn Brown, Therese Stovall, and Patrick Hughes prepared a separate paper to give more details on the carbon reduction potential in the buildings sector.

This analysis focused on reductions in energy use and carbon emissions that can be accomplished through six market transformation policies and from R&D advances. The market transformation policies are:

- Improved building codes for new construction
- Improved appliance and equipment efficiency standards
- Utility-based financial incentive programs
- Low-income weatherization assistance
- The Energy Star® program
- The Federal Energy Management Program

The buildings sector analysis estimated these policies would result in a reduction of 8 quads of energy use by 2025, and R&D advances could result in an additional 4 quads of savings. (A quad is a unit of energy equivalent to 10^{15} Btu.) The authors predicted that the major R&D advance would be solid-state lighting, with advanced geothermal heat pumps, integrated equipment, more efficient operations, and advanced roofs providing smaller contributions. These are summarized in Figure 4.

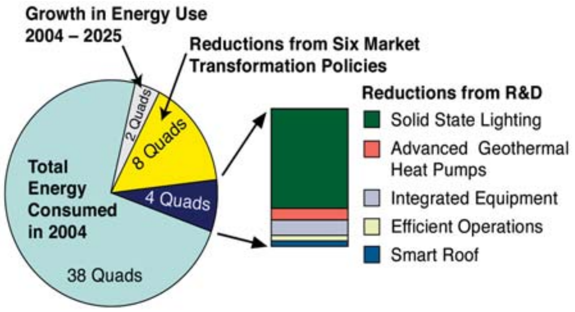


Figure 4. 52 quads buildings sector energy use in 2025 based on the Pew Center scenario.

The original study for the Pew Center estimated that this would be equivalent to an annual savings of 198 MtC/yr by 2025. The authors estimated that adding the impact of solar water heating would save another 0.3 quads or 6.7 MtC/yr. This puts the total estimated carbon savings at approximately 205 MtC/yr by 2025. Because this overlaps with the carbon savings developed in the energy efficiency paper, only the value from the overall efficiency paper is used in the later summation of contributions.

The author of the energy efficiency paper estimates that approximately 40% of the total carbon savings are from buildings. Using the mid-range carbon value, this would correspond to a carbon savings from building energy efficiency of 275 MtC/yr in 2030, compared to a value of 205 MtC/yr in 2025 in the buildings paper. These numbers are fairly consistent, considering that new buildings constructed between 2025 and 2030 should have much higher efficiency than the building stock they replace. In any case, the buildings sector clearly represents a very important opportunity for carbon reduction.

Robb Williamson, NREL PIX 09234

Daylighting and energy-efficient lighting help reduce energy use in buildings. The primary source of light in the Visitor Center at Zion National Park is daylight, and the building's energy management computer adjusts electric light as needed. The Center uses no incandescent or halogen lights, only energy-efficient T-8 fluorescent lamps and compact-fluorescent lamps.

Plug-in Hybrid Electric Vehicles

The transportation sector is responsible for about one-third of U.S. carbon emissions. The overall energy efficiency paper covered total efficiency savings from this sector. However, that study did not specifically describe the potential for plug-in hybrid electric vehicles, which are attracting a great deal of interest due, in part, to the fact that they can help enable renewable electricity generation by virtue of their distributed battery storage. This study analyzed the potential for plug-in hybrid electric vehicles.

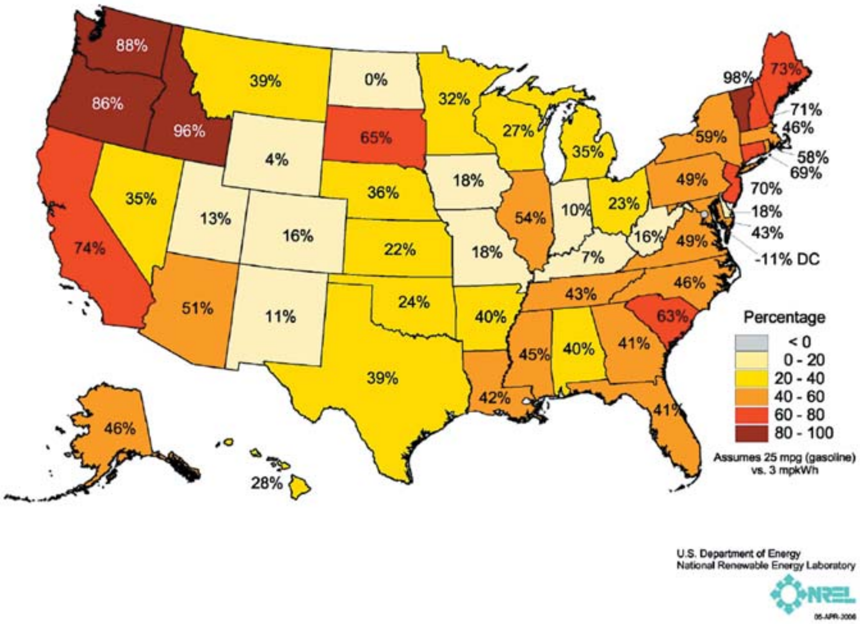


Figure 5. Carbon savings from EVs or PHEVs for operating a vehicle on electricity versus gasoline by state. The national average savings is 42%.

Peter Lilienthal and Howard Brown used the U.S. Environmental Protection Agency (EPA) Emissions and Generation Resource Integrated Database (eGRID) to determine that for each mile driven on electricity instead of gasoline, carbon dioxide emissions would be reduced 42% on average in the United States (see Figure 5.) This is important because coal-based electricity produces a great deal of carbon. (Note that this result may be optimistic, because it does not account for the fact that a plug-in hybrid will typically charge mainly at night, when base load coal plants are more likely to be producing the electricity.) The authors also estimate that running a plug-in hybrid would reduce the average fueling cost of a car by about half, based on a price of $2.77/gallon for gasoline (September 2005) and 8 cents per kWh for electricity (January 2006).

Keith Wipke, NREL PIX 14733

Plug-in hybrids such as this Ford Escape HEV developed by Hymotion are important, not only because of the potential impact this technology can have on reducing gasoline consumption, but also because they can help enable intermittent renewable energy technologies like wind by providing battery storage for electricity from the grid.

Although the impact of plug-in hybrids is not included in our overall summary of carbon savings, plug-ins could help to enable wind power generation. Vehicle batteries being charged overnight are not very sensitive to the exact times they are charged, thereby accommodating the intermittent supply of wind-generated electricity.

Concentrating Solar Power (CSP)

Analysis of CSP by Mark Mehos and Dave Kearney assumed that single-axis tracking parabolic trough solar collectors would provide solar electricity. Although there are other means of using CSP to produce electricity (two-axis tracking parabolic dishes with Stirling engines and solar power towers with two-axis tracking heliostats), parabolic troughs have a track record of producing 350 MW for over 15 years in the southwestern U.S. and are also used in Europe.

As part of a study for the WGA, analysts evaluated the solar resource in the Southwest and then applied various practical filters. They excluded land with a solar resource of less than 6.75 kWh/m^2/day and applied other environmental and land use exclusions. Finally, they eliminated land having a slope of more than 1%. After they applied these filters (Figure 6), they found that CSP could provide nearly 7,000 GW of capacity, or about seven times the current total U.S. electric capacity. When distance to transmission lines was factored in, the authors identified 200 GW of optimal locations.

Analysts expect decreases in technology cost through R&D, scale-up (economies of scale for larger plants), and deployment (or learning-curve benefits). The expected cost reductions are shown in Figure 7. LCOE is levelized cost of energy, or the total costs (nominal costs are those that are adjusted for inflation) divided by the total kWh generated over a power plant’s lifetime.

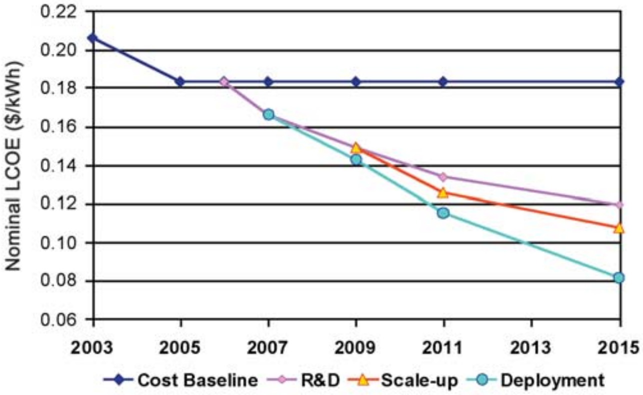


Figure 7. CSP cost reduction curves to 2015.

This 200 GW of capacity can be seen in a supply curve (Figure 8) that plots cost of the technology versus installed capacity.

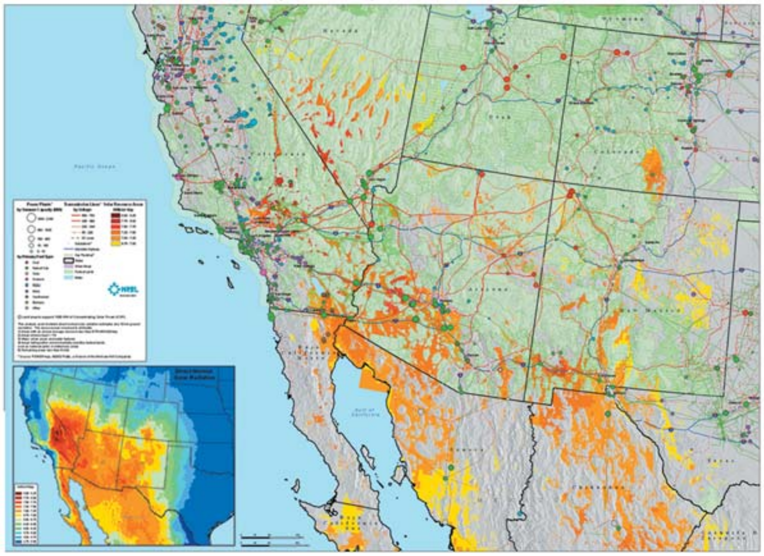


Figure 6. Direct normal solar radiation for U.S. Southwest filtered by resource, land use, and ground slope.

These supply curves were done for three different technology costs for the years 2005, 2015, and 2030. In each case, the graph shows how much deployed capacity occurs at different costs of CSP electricity. The electricity costs depend on the quality of the resource and proximity to transmission lines. Sites with the highest solar resource that are located closest to transmission lines provide electricity at the lowest cost. As capacity increases (as utilities and others develop sites with less solar energy or that are further from transmission lines, for example), the cost of CSP-generated electricity goes up. These curves assume 20%

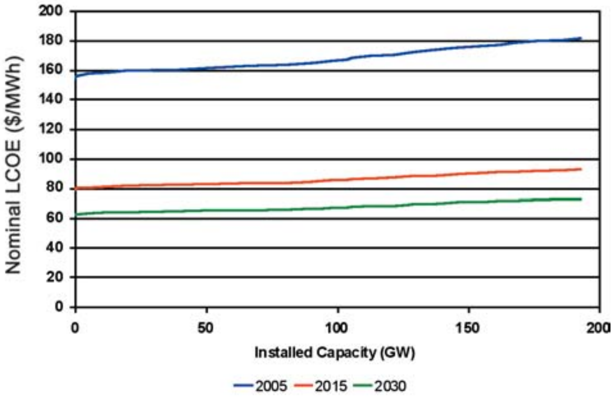


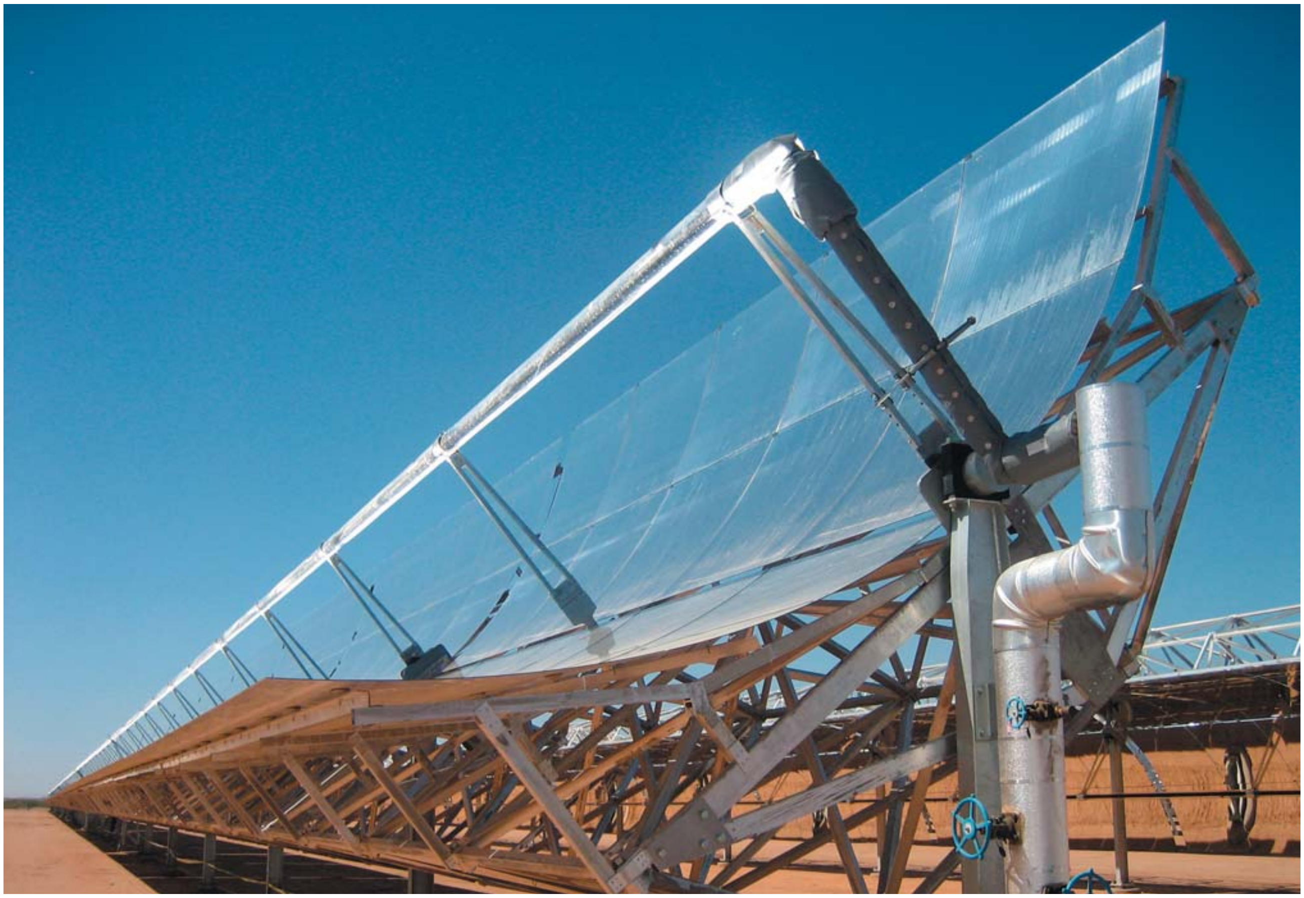
Figure 8. Capacity supply curves for CSP.

of existing transmission capacity is available for use by the CSP plants. Otherwise, cost estimates for new lines are figured at $1,000 per MW per mile. Actual deployed capacity would be a function of time, of course, but the technology costs are likely to drop as shown in Figure 7.

A market study using recently developed NREL market deployment tools, the Concentrating Solar Deployment System Model (CSDS) and the Wind Deployment System Model (WinDS), competed CSP with thermal storage against wind, nuclear, and fossil fuel options. Based on the assumption of an extension of the 30% investment tax credit, this analysis found that 30 GW of CSP could be deployed in the Southwest by 2030.

Because we are interested here in what we can achieve in a carbon-constrained world, the authors ran the model with a carbon value of $35 per ton of CO_2 (a significant

Figure 9. Market deployment of 80 GW of CSP assuming a 30% investment tax credit and a carbon value of $35 per ton of CO_2.


Mark Mehos/NREL

Parabolic trough solar collectors at the recently dedicated 1-MW Saguaro power plant outside Tucson concentrate sunlight onto a receiver tube located along the trough's focal line. The solar energy heats the working fluid in the receiver tube, which vaporizes a secondary fluid to power a turbine. A next-generation version of this collector is being installed at a new 64-MW plant in Nevada.

value, but at one point this was exceeded in the volatile European carbon market). This analysis demonstrated that 80 GW of CSP could then be economically deployed by 2030. This is about a two hundred-fold increase over today's installed capacity in the U.S. This deployment is shown in the map in Figure 9.

Of course, the impact this level of deployment would have on carbon emissions depends on what form of electricity is displaced. The number of GWh produced is a function of the plant capacity factor (the average plant capacity divided by the rated capacity). The CSP study assumed plants with 6 hours of thermal storage and a corresponding capacity factor of 43%, or 0.43. The 80 GW of power deployed by 2030 would correspond to an annual electricity production of 301,344 GWh/yr (80 GW x 8,760 hrs/yr x 0.43). Neglecting the small amount of carbon dioxide released in the construction and operation of a CSP plant and multiplying the 301,344 GWh/yr by 160 metric tons per GWh for the low-end value and 260 metric tons per GWh for the high-end gives a carbon reduction of 48 to 78 MtC/yr by 2030, with an average of 63 MtC/yr.

Photovoltaics (PV)

Although photovoltaic modules, which convert sunlight directly to electricity, can be used in central station applications, they are more commonly deployed on building rooftops. This latter application allows the PV modules to compete against the retail price of electricity, which includes the cost of transmission and distribution, thus better offsetting the higher price of PV. Whereas parabolic troughs require high levels of direct (or beam) radiation so that it can be focused onto the receiver tube, rooftop PV modules are stationary and do not concentrate sunlight. Thus they capture both diffuse and direct radiation and can operate outside the Southwest. (Although total solar radiation levels are lower in northern U.S. locations than in the Southwest, they are typically higher than in Germany, which has a very robust PV market, albeit with high electricity prices and strong government incentives.) Figure 10 shows the total solar radiation resource on a surface facing south and at a tilt equal to the local latitude.

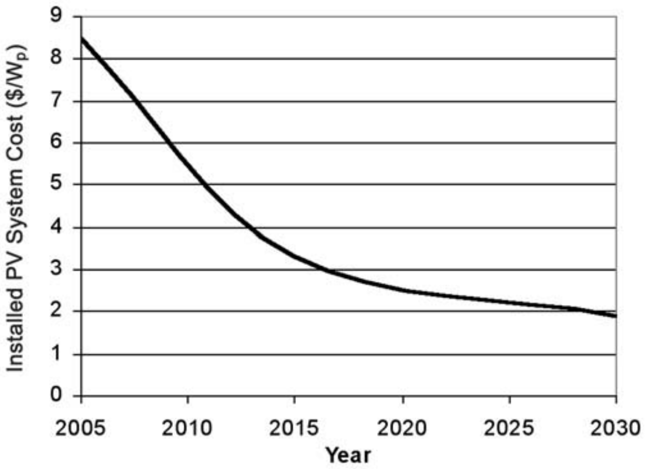


Figure 11. PV cost reduction goals to 2030.

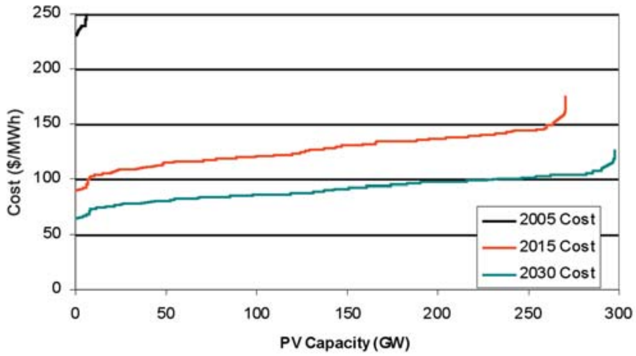


Figure 12. PV capacity supply curves based on year 2005, 2015 and 2030 values.

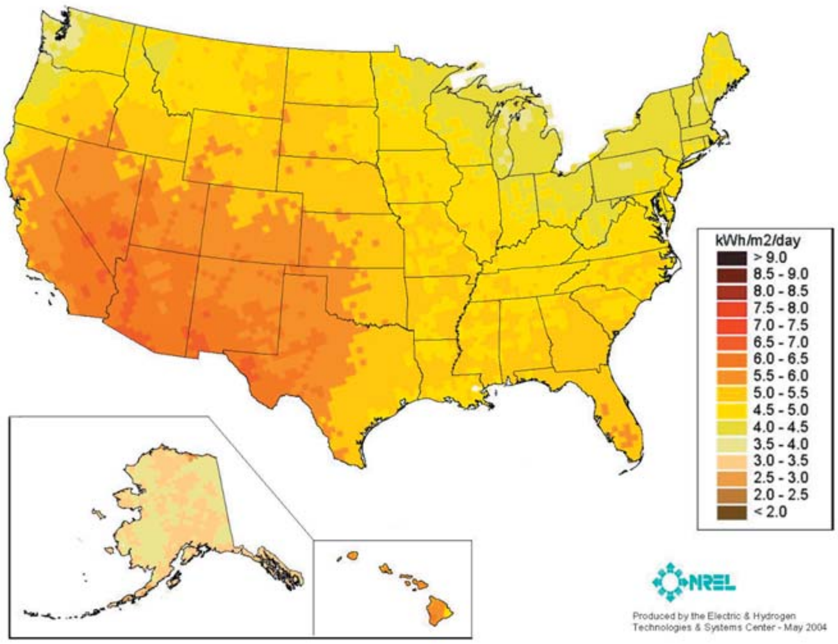


Figure 10. U.S. map of the solar resources for PV using flat, south-facing surfaces at tilt equal to latitude.

After rooftops are filtered for shading and inappropriate orientation, estimates of roof area suitable for PV in the United States range between 6 billion and 10 billion square meters. This study by Paul Denholm, Robert Margolis, and Ken Zweibel began by looking at what could be captured by 2030 by using the lower value for suitable roof area. Current costs of PV are high but are dropping rapidly as manufacturing techniques improve and the market grows. Figure 11 shows the cost reduction goals for roof-mounted PV systems.

Because photovoltaic (PV) systems are typically sited on roofs and connected to the electrical grid, PV modules can compete against the retail price of electricity, offsetting the technology's high cost. Oberlin College's Adam Joseph Lewis Center for Environmental Studies features a south-facing curved roof covered in electricity-producing PV panels.

Robb Williamson, NREL PIX 10864

Figure 12 shows estimated PV supply curves for technology costs based on year 2005, 2015, and 2030 values. This shows costs in excess of 28 cents per kWh for today's technology, and capacity as high as 300 GW for costs ranging from 6 to 12 cents per kWh.

Analysis suggests that 10% of electric grid energy by 2030 could be supplied by PV without creating grid management issues. This would be equivalent to 275 GW, based on the EIA projection for 2030 grid electricity less the impact of energy efficiency measures. However, PV manufacturers are currently producing modules at capacity. There are concerns about how quickly the PV industry could scale up and produce such a large quantity of modules.

The PV industry has developed a roadmap that sets a deployment goal of 200 GW_p in the United States by 2030, and this lower value was used as a potential scenario. With any of the renewable supply technologies, it is difficult to estimate deployment rates because this will depend on national commitment, policy incentives, etc. However, the authors estimated how the deployment of 200 GW_p of PV would occur between today and 2030. Figure 13 shows scenarios for both the PV production capacity and installations between now and 2030 for achieving 200 GW_p of deployment. This indicates that the high growth rate of PV production will rise slightly and then decline. PV installations will occur much more rapidly nearer to 2030 due to the expected drop in prices.

Rooftop PV modules are not typically designed to track the sun, and this analysis assumes that the PV systems are grid-connected and use no battery storage, so the average power output is much less than the peak capacity. The average capacity factor in this study was 17%.

Compared to the average U.S. electric mix, the annual carbon reduction at the low-end conversion of 160 metric tons per GWh by 2030 is therefore 200 GW x 8,760 hrs x 0.17 x 160 metric tons C/GWh = 48 MtC/yr. The value at 260 metric tons of carbon per GWh is 78 MtC/yr. The resulting range is 48 to 78 MtC/yr, with an average of 63 MtC/yr. (This value is coincidentally the same as the CSP value, despite the differences in peak power outputs and capacity factors, which offset each other.) The 200 GW_p of PV would represent 7% of U.S. grid electric energy by 2030, accounting for the impact of energy efficiency measures. It is important to note that the 200 GW potential represents about a five hundred-fold increase over currently installed capacity in the U.S., a much larger expansion than for the other renewable technologies covered in this study.

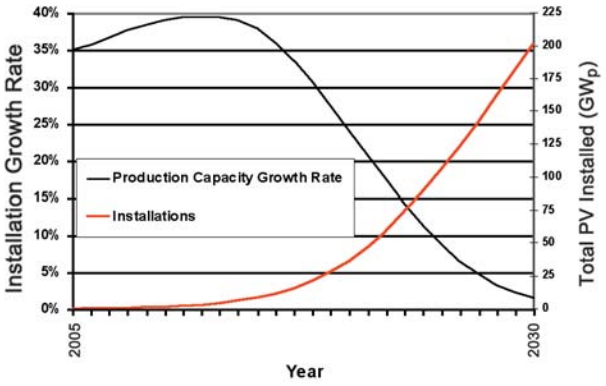


Figure 13. PV production and field deployment scenario to 2030.

Wind Power

Over the last several years, wind power has experienced the highest deployment of non-hydro renewable technologies because of its low cost. U.S. capacity is now over 10,000 MW, and 2,500 MW was installed in 2005. The map in Figure 14 shows how this wind resource is distributed throughout the United States. It is concentrated in the Rocky Mountain and Great Plains states, but the resource is also very high along the Sierras and the Appalachians. The U.S. is well endowed with wind sites of class 3 and higher.

Figure 15 shows the expected cost reductions for wind power for class 6 wind sites (17.5 to 19.7 mph measured at a 50 m height). Costs are already competitive at about 4 cents per kWh and are expected to drop to under 3 cents per kWh by 2030.

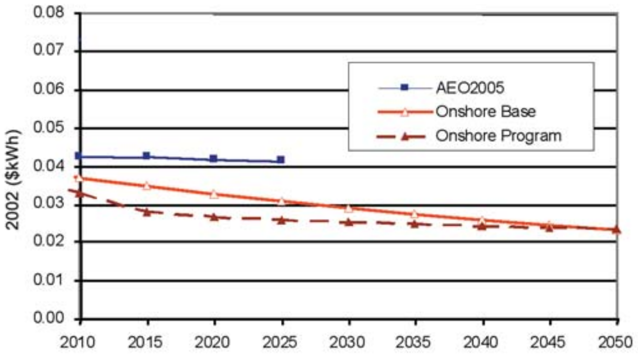


Figure 15. Expected reductions in the cost of wind power for class 6 wind sites to 2050. The lower red curve (Onshore Program) denotes the low-wind speed turbine (LWST)/Wind Program goal to reduce costs. The Onshore Base red curve is the "base case" without the LWST.

Like CSP, the wind study by Michael Milligan had the advantage of having a market simulation model, WinDS, available that was developed by the National Renewable Energy Laboratory. This model looks at various regions

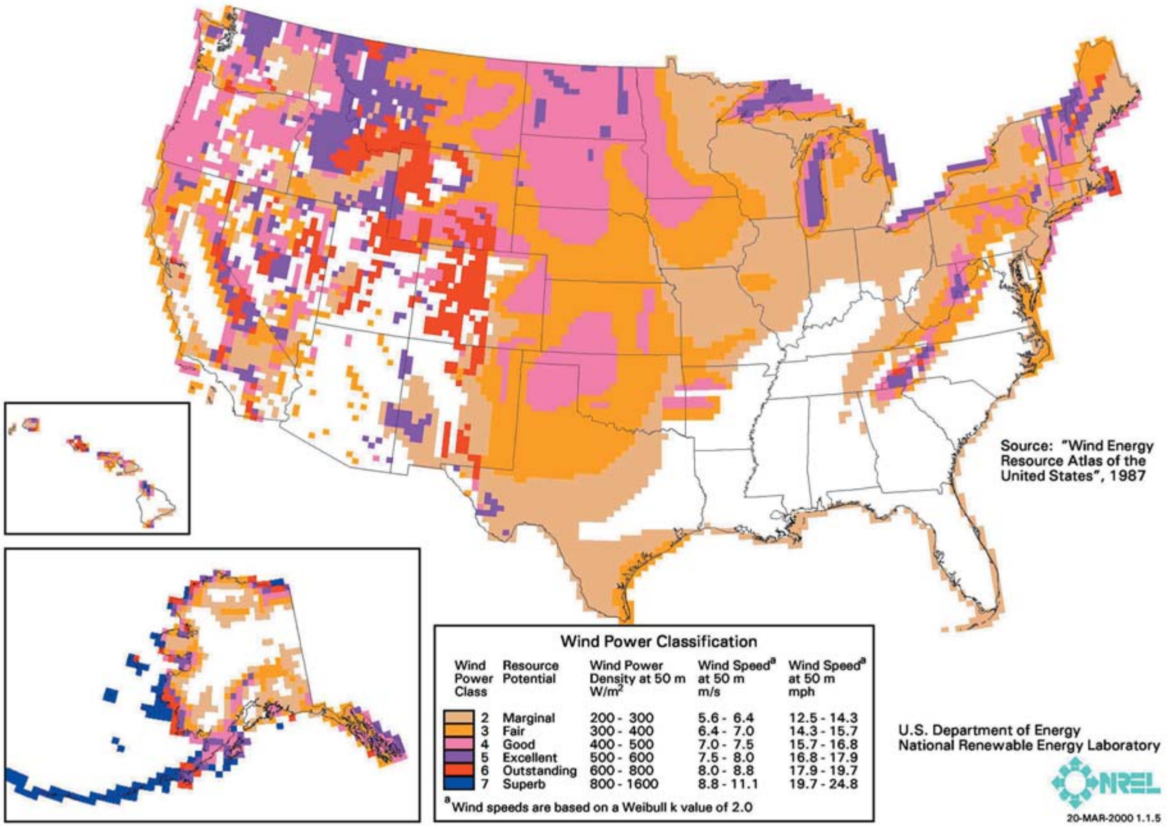


Figure 14. Wind resource map.

in the United States with GIS representations of wind resource and transmission lines and compares the economics of wind to other energy options, selecting the least-costly alternative. The model runs for this study assumed the existing production tax credit of 1.9 cents per kWh would be renewed until the year 2010 and then would be phased out linearly until the year 2030. Offshore wind was not considered. The results of this study showed the market deployment curve of Figure 16.

The wind capacity was limited to 20% of expected national grid electric energy, or 245 GW, because analysts believed that dispatchability could become difficult at higher penetrations without storage, even though the market simulation model indicated that higher amounts are possible. This represents about a twenty-five-fold increase over today's U.S. wind capacity. A map illustrating what this deployment might look like is shown in Figure 17.

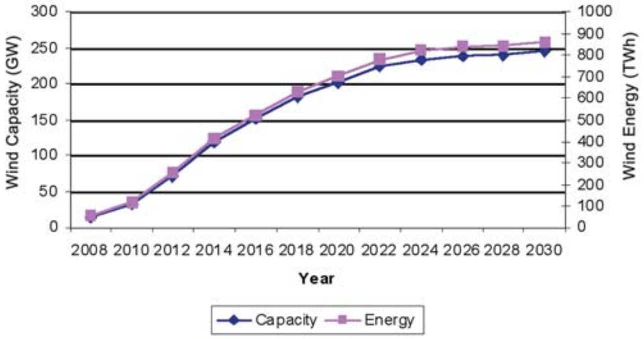


Figure 16. Wind market penetration to 2030 based on market simulation model.

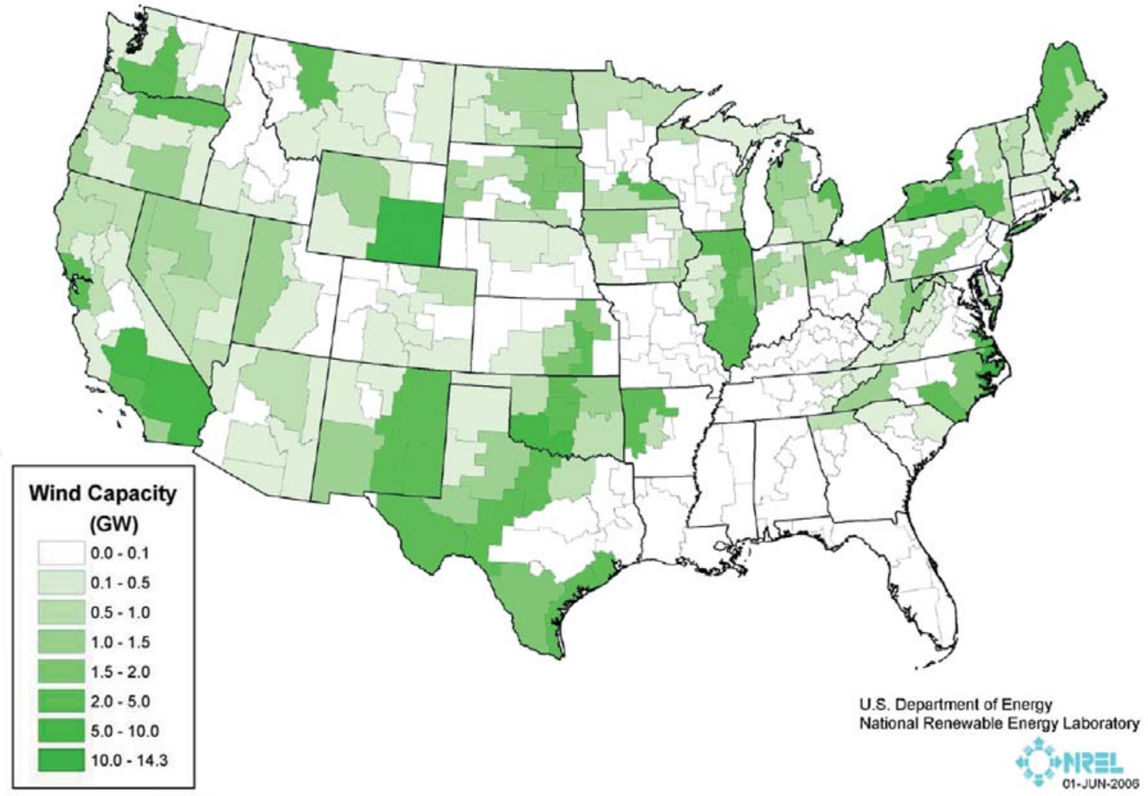


Figure 17. The WinDS model scenario of approximate wind locations for 20% penetration of electric grid (energy).

Unlike PV, analysts assume wind will have a rapid market penetration in the near term due to its competitive cost, and then will level off as less favorable wind locations are exploited and as grid dispatchability issues become significant.

Capacity factors for wind vary from 30% for Class 3 wind (14.3 to 15.7 mph) to 49.6% for Class 7 (19.7 to 24.8 mph). Assuming an average capacity factor of 40%, 245 GW corresponds to an annual carbon reduction of 245 GW x 8760 hrs x .40 x 160 metric tons C/GWh = 138 MtC for the low-end carbon conversion case. The high-end conversion would yield 224 MtC/yr. Thus the range for wind is 138 to 224 MtC/yr, with an average of 181 MtC/yr. This is shown in Figure 18.

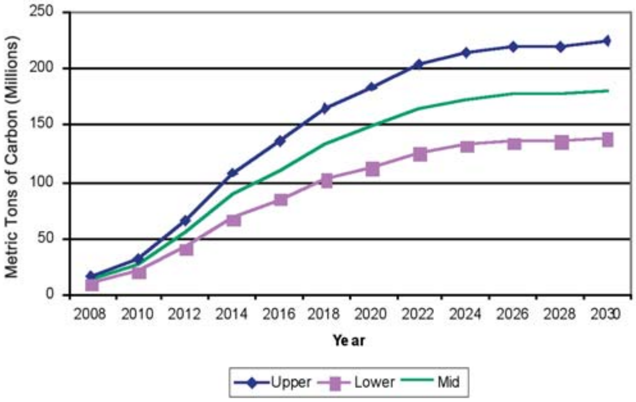


Figure 18. Carbon displacement to 2030 for the upper, lower, and mid-carbon cases.

Jennifer Harvey, NYSERDA, NREL PIX 14399

Each 1.65 MW wind turbine at the Maple Ridge Wind Farm near Lowville, New York, generates enough electricity to power about 500 homes.

Biomass

Ralph Overend and Anelia Milbrandt took the Oak Ridge National Laboratory Billion Ton Study conclusions regarding the amount of biomass available nationwide in 2025 (which is an aggressive scenario based on improved farm practices and land use for energy crops) and assumed that the ratio of electric output to biomass would be the same as that found in the WGA Clean and Diversified Energy Study of biomass electricity potential by 2015 in 18 western states. The U.S. lignocellulosic (nonfood crop) biomass resource, based on work by Milbrandt, is shown in Figure 19. The resource, which is known on a county-by-county basis, is concentrated in the corn belt and urban centers. Resources considered for this study included agricultural residues (e.g., corn stalks and wheat straw), wood residues (from forests and mill wastes), and urban residues (e.g., municipal solid waste and landfill methane). In addition, although it is not included in Figure 19, the Billion Ton Study included future energy crops like switchgrass. The authors assumed that the generation of electricity from biomass would employ the lowest-cost power plant option. For plants rated at 15 megawatts electrical (MW$_e$) or more, this tended to be integrated gasification/combined cycle (IGCC), and for plants rated at less than 15 MW$_e$, this tended to be either a stoker with a steam turbine or a gasifier-internal combustion engine combination.

The WGA study concluded that the 170 million metric tons of biomass available annually in 18 western states could produce 32 GW of electricity by 2015. However, as shown in the supply curve of Figure 20, only 15 GW of this is available at a cost of less than 8 cents per kWh, so 15 GW is taken to be the electric output corresponding to 170 million metric tons of biomass.

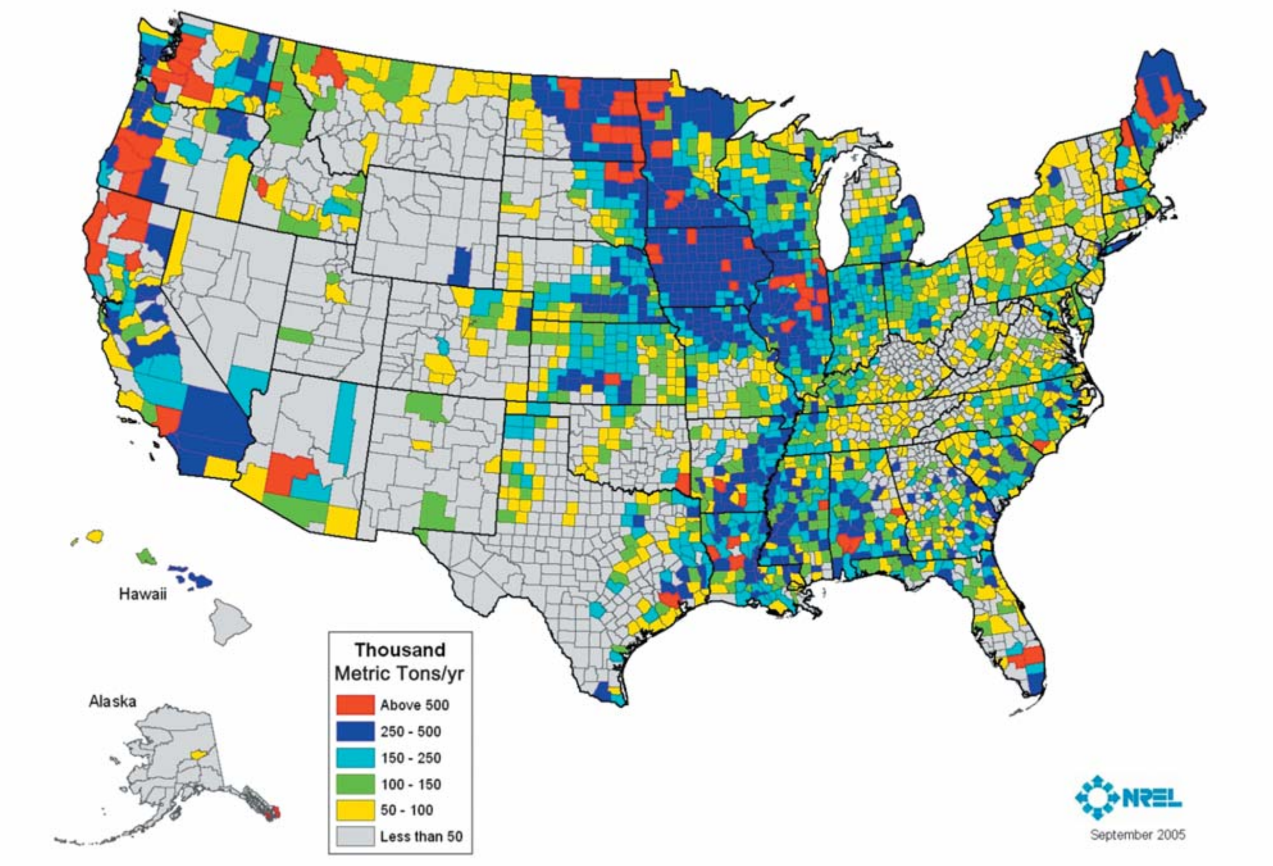


Figure 19. Map of U.S. biomass resource showing dry metric tons of biomass per year for each county.

Overend and Milbrandt assumed that the same ratio of power production to dry biomass would exist for the year 2025 1.25 billion ton national resource, thus yielding 110 GW. This represents about a tenfold increase over today's biomass electricity capacity. Using a capacity factor of 90%, the 110 GW corresponds to an annual carbon reduction of 110 GW x 8760 hrs/yr x 0.9 x 160 metric tons C/GWh = 139 MtC for the low-end carbon case. For the high-end case, the result is 225 MtC and the average is 183 MtC/yr. This would be at estimated costs ranging from 5 to 8 cents per kWh. The WGA analysis was only for the year 2015 (although the western resource was assumed to be fairly well tapped by that date) and the national resource is a year-2025 estimate, so using these results for 2030 should be conservative. Also, biomass can provide base load electricity, so it could compete directly against coal plants and thus provide a carbon displacement closer to the higher estimate.

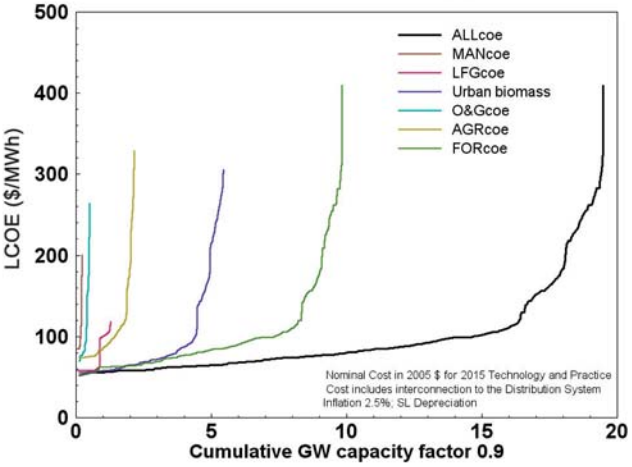


Figure 20. Capacity supply curves for biomass based on 18 western states. Key to figure curves: Man = Manure, LFG = Landfill Gas, Urban Biomass = Municipal Solid Waste, O&G = Orchard and Grapes (California only), AGR = Agricultural Residues, FOR = Forestry Resources.

Although this project involved a separate study of biofuels (see the next section), Overend and Milbrandt also considered the implication of using the biomass to produce liquid fuels instead of electricity. They concluded that the carbon displacement would be significantly less than for the electricity production case. Thus, from the standpoint of reducing carbon emissions, it is better to use biomass to produce electricity. This would especially be the case if carbon were captured and sequestered from the biomass (not assumed in this study). Biofuels have high values as a replacement for imported oil, however, and Overend and Milbrandt point out that biomass will be used for a combination of electricity and biofuels.

The 21 MW Tracy Biomass Plant uses wood residues discarded from agricultural and industrial operations to provide the San Francisco Bay Area with base load capacity.

Andrew Carlin, Tracy Operators, NREL PIX 06665

All photos courtesy NREL with the assistance of Aspen Skiing Co. for the large array; and Dave Parsons, Pacific Gas & Electric, and Warren Gretz for the smaller photos (top to bottom, respectively)

Biofuels

Transportation contributes about 32% of U.S carbon emissions. Although using biomass to produce electricity can produce greater carbon reductions than using biomass to make liquid fuels, there are other renewable means available to produce electricity, and there is considerable national interest in displacing imported oil. The biofuels study by John Sheehan looked at the use of crop residues and energy crops for producing cellulosic ethanol.

The author considered only one means for producing ethanol from these crops—biological conversion via fermentation. Figure 21 shows the target cost reductions for ethanol production from this process. These are wholesale costs and are given in terms of gallons of gasoline equivalent and account for the fact that a gallon of ethanol contains only about two-thirds as much energy as a gallon of gasoline.

Figure 22 shows ethanol supply curves for 2015 and 2030. Figure 23 shows the equivalent carbon savings based on reductions of 7 kilograms (kg) and 8 kg of CO_2 (or 1.9 and 2.2 kg carbon) per gallon of gasoline equivalent, respectively, for agricultural residues and switchgrass.

Charles Bensinger, Renewable Energy Partners of New Mexico, NREL PIX 13531

Biofuels can displace imported oil for transportation. This triple biofuels dispenser at the Baca Street Biofuels Station in Santa Fe, New Mexico, offers consumers a choice of renewable transportation fuels.

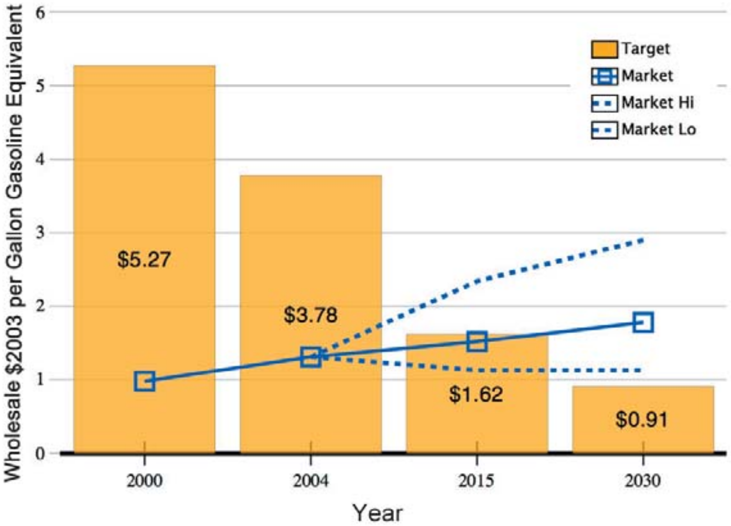


Figure 21. Target costs of cellulosic ethanol from fermentation to 2030.

From Figure 23, while there is the potential to displace 70 MtC/yr by 2030, the author estimates that only 58 MtC/yr can be displaced economically. This would save 28 billion gallons of gasoline in 2030, which is about 20% of today's U.S. gasoline consumption, and would correspond to about a tenfold increase over today's ethanol production. If these savings were combined with more efficient vehicles and plug-in electric hybrids, the result could represent a significant portion of the future U.S. liquid fuel requirement.

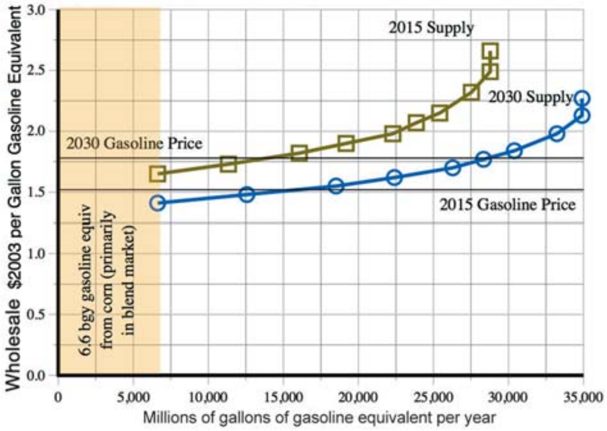


Figure 22. Cellulosic ethanol supply curves for 2015 and 2030 as a function of wholesale prices per gallon of gasoline equivalent.

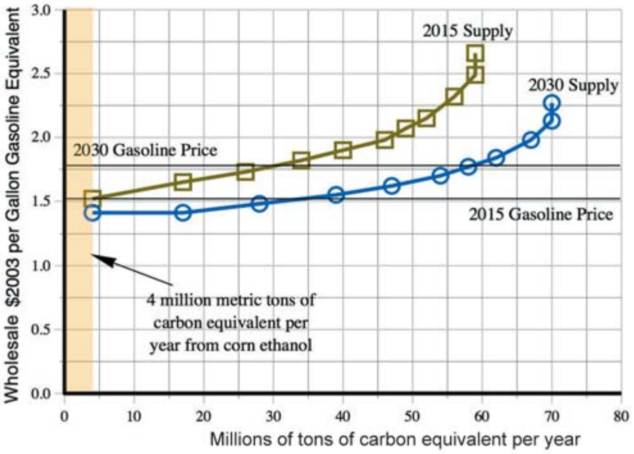


Figure 23. Carbon saving supply curves for cellulosic ethanol for 2015 and 2030.

Geothermal Power

There are currently 2,800 MW of geothermal electricity design capacity in the United States, although the current peak production is about 2,200 MW owing to declines in steam pressure at the world's largest plant, The Geysers. All of these plants, and in fact all geothermal power plants in the world, use hydrothermal resources, which are naturally occurring reservoirs of hot water and steam located within a few thousand feet (or about a kilometer) of the surface. Most of the U.S. plants are located in California and Nevada. They all use hot water or steam from below the surface to drive either a Rankine steam cycle or, for lower temperature resources, a Rankine power cycle using a fluid with a lower boiling point than water, such as isobutane or pentane. (The latter is called a "binary cycle.") Exploitation of future geothermal resources is focused on drilling to greater depths than today's plants. Figure 24 shows a map of temperatures at a 6-kilometer (km) depth.

The WGA Clean and Diversified Energy Study estimated that there will be about 6,000 MW of new power available from hydrothermal resources by 2015 and a total of 13,000 MW available by 2025. The power potential increases if one considers other resource types that have thus far not been tapped to produce geothermal electricity. So-called "enhanced geothermal systems," or EGS, involve the use of water injection under pressure to add water and permeability to rock that is hot but dry or lacking in porosity. In their geothermal paper, Martin Vorum and Jeff Tester divide this into "sedimentary EGS," which means the expansion of existing hydrothermal reservoirs, or "basement EGS," which means deep, hot dry rock. There is also considerable interest in using hot water from depleted oil and gas wells near the Gulf Coast.

Vorum and Tester estimate that a total of 100 GW (at costs of under 10 cents per kWh) would be available from the various resources by 2050 as follows:

- 27 GW from hydrothermal
- 25 GW from sedimentary EGS
- 44 GW from oil and gas fields
- 4 GW from basement EGS

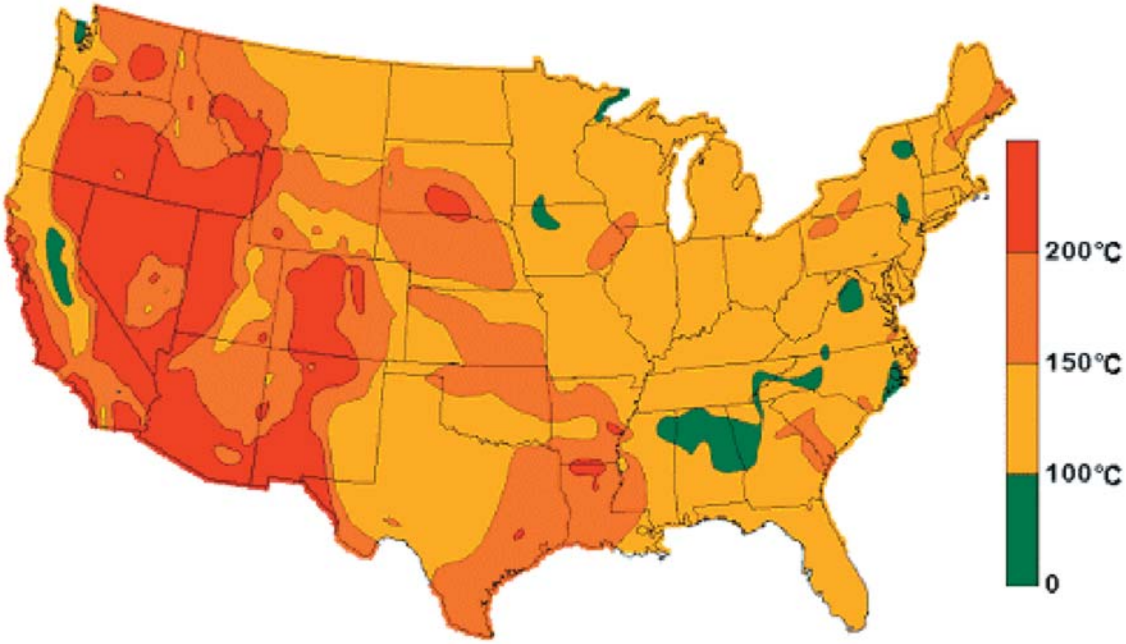


Figure 24. Temperatures at 6-km depth. (Source: Blackwell, Southern Methodist University, 2004)

The Mammoth Lakes Power Plant is located in a picturesque area of northern California. Binary-cycle geothermal power plants release no carbon dioxide or water vapor plumes and blend into the environment.

J.L. Renner, INEEL, NREL PIX 07670

Because most high-temperature hydrothermal resources in the United States have already been tapped, the costs assumed the use of binary cycles. These costs are shown in Table 1.

Table 1.

Estimated costs of geothermal power production.

	Hydrothermal Binary	EGS Binary
Reference Case Bases		
Reservoir Temperature (ºC)	150	200
Well Depths (feet)	5,000	13,000
LCOE as ¢ per kWh		
LCOE — as of 2005	8.5	29.0
LCOE — as of 2010	4.9	
LCOE — as of 2040		5.5

Supply curves are shown in Figure 25.

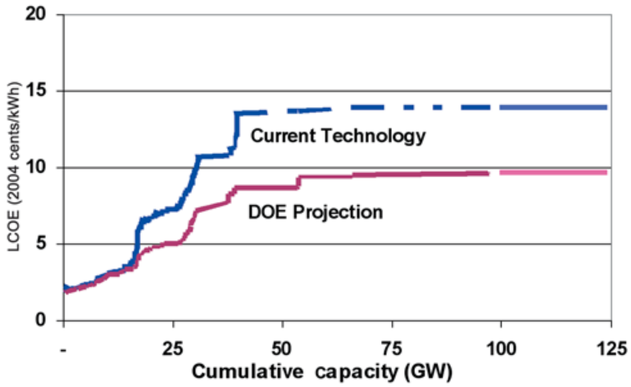


Figure 25. Geothermal supply curves.

Runs of the National Energy Modeling System (NEMS) predicted geothermal plants could produce one-half of the 100 GW, or 50 GW, by 2030. This represents about a twenty-fold increase over today's U.S. geothermal electric capacity. (In the absence of a DOE program to reduce costs, this would drop to 30-35 GW.)

Assuming climate change concerns spur continued research to lower costs and using a 90% capacity factor (quite conservative for existing geothermal plants), the carbon displacement by 2030 is 50 GW x 8760 hrs x 0.90 x 160 metric tons C/GWh = 63 MtC/yr for the low-end carbon case. The result for the high-end conversion is 103 MtC/yr, and the mid-range value is 83 MtC/yr. As in the case of biomass electricity, a geothermal plant runs 24 hours per day, seven days per week and can provide base load power, thus competing against coal plants. So the high-end value may be realistic for geothermal, although the mid-range value is used in our summation. On the other hand, a substantial amount of the geothermal resource being tapped in this study is non-hydrothermal. The assumption that new resources will be successfully tapped adds significantly to the uncertainty of the estimates.

Summary of Contributions

These studies were done mostly independently. Although we made them as uniform as possible, different information and analysis tools were available for each of the different resources. NREL's new market deployment analysis tools were only available for wind and concentrating solar power. The concentrating solar power results assumed a carbon value of $35 per ton of CO_2. The wind result limited the penetration to 20% of grid electric generation in 2030, after accounting for potential efficiency improvements. And the PV potential was limited by estimated production capability.

The purpose of this study was to consider a renewables-only scenario that focuses on what renewable energy can do in the absence of any new nuclear or coal gasification (with carbon capture) plants. These non-renewable options are potential means for addressing climate change, but they require longer lead times than the renewable options and they present other environmental problems. The costs of new nuclear plants and coal gasification plants with carbon capture and storage will likely be sufficiently high that renewables will be very competitive economically.

Energy efficiency improvements can be viewed either as lowering the business-as-usual curve or as a wedge of displaced carbon. We will use the result of the overall energy efficiency study because this dealt with energy savings from efficiency improvements in electricity, natural gas, and oil using a reasonably consistent methodology. As described earlier in this overview, if we average the energy efficiency results for the lower (national electric mix) and upper (coal) cases, the carbon savings is 688 metric tons of carbon per year by 2030.

One area where we must avoid double-counting is with biomass and biofuels. Although converting biomass to electricity provides the greater carbon reduction, there is a strong national interest in displacing foreign oil. So for the sake of this analysis, we will assume that biomass for fuels takes precedence over biomass for electricity. The biofuels study was based on the use of crop residues and energy crops and resulted in 58 MtC/yr displacement. If we neglect these types of biomass in the projected 1.25 billion metric tons used in the biomass study, we are left with 41% of that biomass available to produce electricity. Using all the biomass to produce electricity provided a carbon displacement of 183 MtC/yr, and 41% of this yields 75 MtC/yr.

Table 2 summarizes the various potential carbon reductions. If we show all the different contributions as wedges on the same graph, we obtain Figure 26. Approximately 57% of the carbon reduction contribution is from energy efficiency and about 43% is from

Energy efficiency measures can allow U.S. carbon emissions to remain about level through 2030, whereas the renewable supply technologies can provide large carbon reductions.

renewables. Energy efficiency measures can allow U.S. carbon emissions to remain about level through 2030, whereas the renewable supply technologies can provide large carbon reductions. The pie chart in Figure 27 shows the relative contributions of different renewable energy technologies.

Table 2.
Potential carbon reductions (in MtC/yr in 2030) based on the middle of the range of carbon conversions.

Energy efficiency	688
Concentrating solar power	63
Photovoltaics	63
Wind	181
Biofuels	58
Biomass	75
Geothermal	83

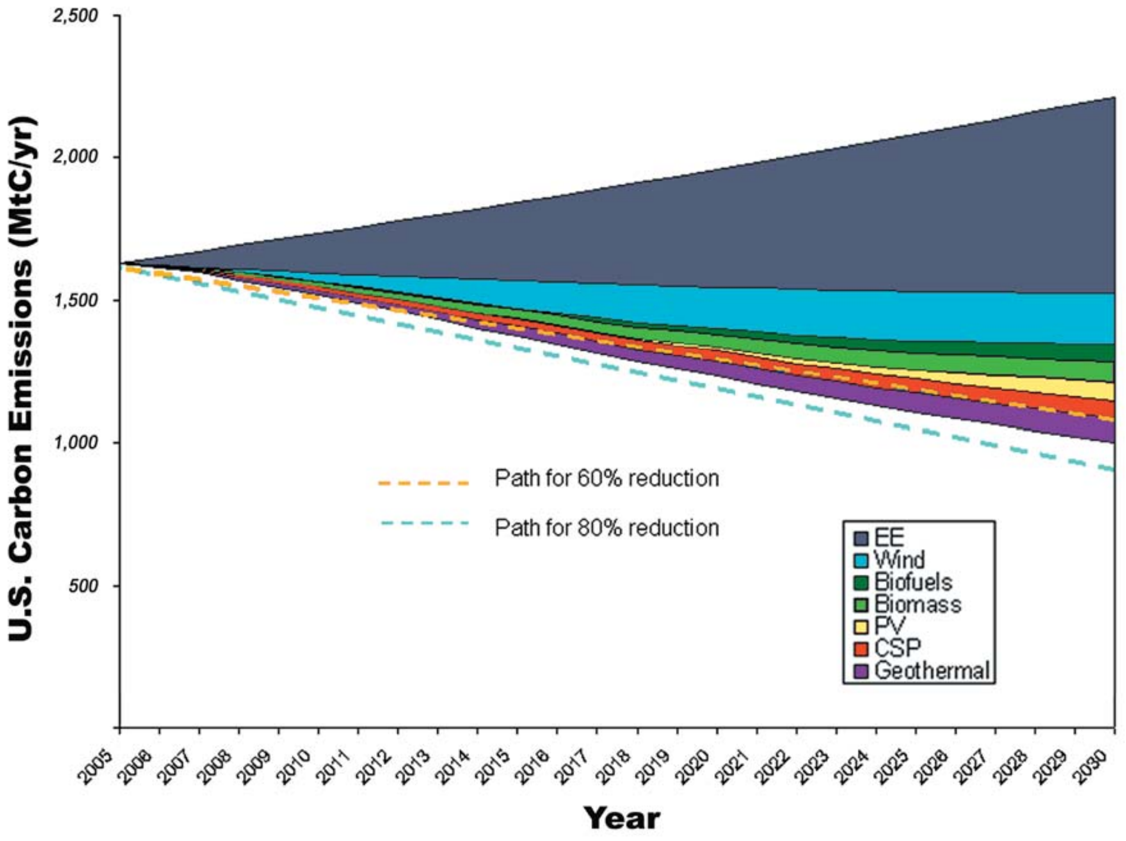


Figure 26. Potential carbon reductions in 2030 from energy efficiency and renewable technologies and paths to achieve reductions of 60% and 80% below today's emissions value by 2050.

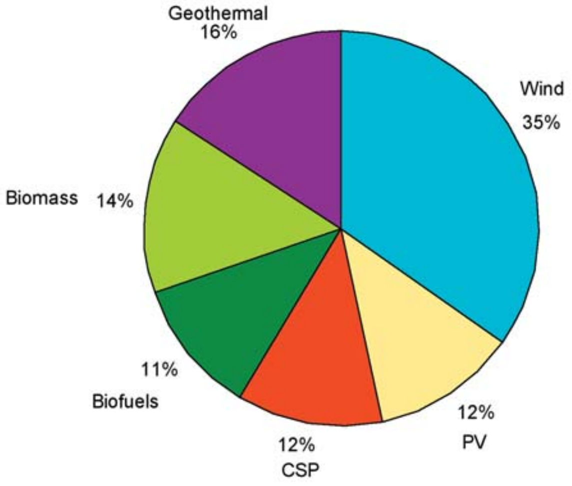


Figure 27. Pie chart showing relative contributions of the various renewables in 2030.

The various contributions for the year 2030 total between 1,000 and 1,400 MtC/yr (with a mid-range value of about 1,200 MtC/yr), which would be on target to achieve carbon emissions reductions of between 60% and more than 80% from today's value by 2050. The carbon reductions in 2015 range from 375 to 525 MtC/yr, with a mid-range value of 450 MtC/yr.

How much renewable electricity does this represent relative to what is needed? The current U.S. annual electric output is 4,038 terawatt-hours (TWh), and the EIA business-as-usual (BAU) projection is a value of 5,341 TWh by 2030 of which 4,900 TWh is from fossil fuels. The energy efficiency paper estimates an annual savings of 980 TWh in 2025, which we conservatively extrapolate at an economic growth rate of 1.2% per year (the EIA BAU growth rate) to 1,038 TWh in 2030. This leaves a total electric energy generation in 2030 of 5,341 TWh – 1,038 TWh = 4,303 TWh. The following table lists the annual electricity generation in TWh for the various renewable energy technologies:

Table 3.

Potential electricity contributions from the renewable technologies in 2030. Percentages are based on the projected national electric grid energy reduced by the energy efficiency measures described in this report.

Technology	**Annual Renewable Electricity in 2030 (TWh)**	**Percent of Grid Energy in 2030**
Concentrating Solar Power	300	7.0
Photovoltaics	300	7.0
Wind	860	20.0
Biomass	355	8.3
Geothermal	395	9.2
Total	**2,208**	**51.5**

Summing the renewable electricity contributions results in about 50% total grid penetration (after accounting for efficiency improvements) in 2030. This is significantly higher than a commonly stated goal of "30% by 2030," but this may not account for a reduction in electric energy production from aggressive efficiency measures. The total renewable electricity contribution above would represent about 40% of the EIA electricity projection without accounting for our efficiency improvements. This may seem high, but it is consistent with what is needed to mitigate climate change with renewables.

If all these renewables were deployed together, because they would compete against each other, the total potential would be somewhat less than shown here. On the other hand, the various renewables occur in different regions and apply to different sectors. The map in Figure 28 shows how energy efficiency and the various renewables covered in the study could be distributed throughout the United States.

Concentrating solar power uses direct solar radiation in desert regions to supply electricity at the busbar and peaks in the early evening due to 6 hours of storage. It can also be augmented with natural gas to improve dispatchability. PV on buildings uses total solar radiation in populated areas to provide electricity on the demand side and, with no storage, peaks earlier in the day. Wind often provides greater energy at night than during the day and was competed against CSP in the market penetration model. Biomass and geothermal provide base load power. Biofuels, of course, compete against gasoline. Even if a rigorous integrated market penetration model was currently available, it might not necessarily give the correct mix of technologies. There will be some interest in maintaining a diverse portfolio of renewable options aside from purely economic considerations, and we are already seeing this with many state renewable portfolio standards.

The electric production technologies each had limited grid penetrations, with wind being the highest at 20%. However, at some times of the year, the combined renewable electric output could be enough to impact base load power production, which often cannot be rapidly turned down, so further analysis of an integrated renewable energy mix is needed.

These studies did not consider ocean power or thermal energy from renewables. Solar industrial process heat and solar heating/cooling could potentially provide additional carbon reductions. Although the studies included six-hour thermal storage for concentrating solar power (thermal storage is relatively inexpensive), they did not include electrical storage (e.g., batteries for PV or adiabatic compressed air energy storage for wind). Also, the studies did not consider superconducting transmission lines, which would allow wind power to be distributed over larger distances and could allow concentrating solar electricity to be exported outside the Southwest. Finally, we did not consider the various forms of ocean energy because there is currently very little work on these technologies in the U.S. All of these could increase the carbon reduction potentials in 2030 above those estimated in this report.

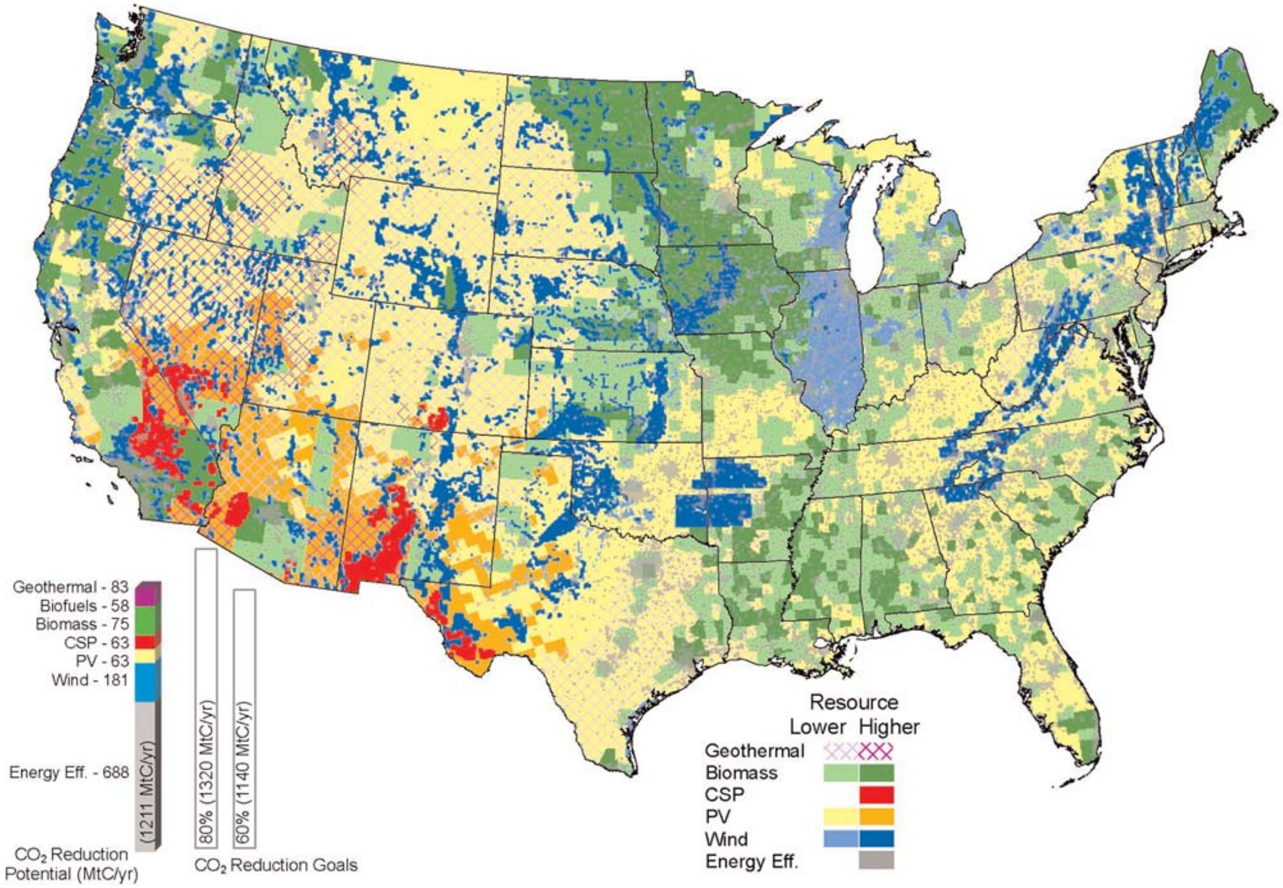


Figure 28. U.S. map indicating the potential contributions by energy efficiency and renewable energy by 2030. CSP and wind are based on deployment scenarios; other renewables indicate resource locations.

Conclusions

This special series of papers examines the extent to which energy efficiency and renewable technologies could potentially reduce U.S. carbon emissions by 2030 in an aggressive but achievable scenario. It shows that these technologies have the potential to be on track to achieve between a 60% and 80% reduction below today's level by 2050, depending on the electricity sources displaced. A national commitment that includes effective policy measures and continued R&D to reduce costs will be needed to fully realize these potentials. About 57% of the carbon displacement is provided by energy efficiency and 43% by the various renewable technologies. Of the renewables contribution, about one-third is due to wind power, and the rest is roughly evenly divided among the other technologies studied.

There are uncertainties associated with the ppotentials estimated in the papers, and, because these were primarily individual technology studies, there is some uncertainty associated with combining them. The results strongly suggest, however, that energy efficiency and renewable energy technologies have the potential to provide most, if not all, of the U.S. carbon emissions reductions that will be needed to help limit the atmospheric concentration of carbon dioxide to 450-500 ppm. We hope this work will convince policy makers to seriously consider the contributions of energy efficiency and renewable technologies for addressing global warming.

Because global warming is an environmental crisis of enormous scale, we simply cannot afford to wait any longer to drastically reduce carbon emissions. It certainly makes sense to attack a problem of this magnitude on many fronts. We should continue work on areas such as coal gasification, geologic sequestration of carbon dioxide, cost reduction of renewables, high-efficiency transmission, advanced storage, and development of breakthrough technologies. We should also continue to improve our analyses.

But it is most important that we immediately begin an aggressive campaign to drastically reduce carbon emissions with the technologies we already have. Energy efficiency and renewable energy technologies are available for large-scale deployment today to immediately begin to tackle the climate change crisis.

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Additional references appear at the end of each study

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Tackling Climate Change in the U.S.

Potential Carbon Emissions Reductions from Overall Energy Efficiency by 2030

by **Joel N. Swisher, Ph.D., P.E.**
Rocky Mountain Institute


Doug Lockhart, University of California, NREL PIX 14839

The Molecular Foundry at Lawrence Berkeley National Laboratory (LBNL), which incorporates state-of-the-art energy efficiency technologies and strategies, is designed to consume 30% less energy than the already-stringent California requirement for laboratory buildings.

Assuming no change in carbon intensity of energy supply, the total achievable potential for cost-effective carbon emissions reduction from energy efficiency in 2030…is enough to essentially offset carbon emissions growth.

Energy efficiency is the use of technology to provide greater access to energy services with less consumption of energy resources such as fuel and electricity. Energy services include mobility, thermal and visual comfort in buildings, sanitation, agricultural production, and the motive power and thermal processes required for industrial production.

Efficiency is not the same as conservation. Conservation entails doing without energy services through frugal behavior or deprivation. Efficiency entails doing more with less.

The ability of energy efficiency to help meet demand for energy services, and to replace some energy supply resources, enables us to treat efficiency as a resource to substitute for fossil fuels and reduce CO_2 emissions. Because the efficiency resource depends only on innovation, integrated design, and the application of technology—which is expanding—this resource can become more abundant over time, just as we are depleting fossil fuels and reaching the limits of our planet's ability to absorb their by-products.

The efficiency resource is large but diffuse. Efficiency potential exists everywhere that energy is used, including buildings, vehicles, factories, and farms. The efficiency resource that is already realized is found in this same diffuse distribution, which makes it difficult to measure, even in retrospect.

One simple measure is primary energy consumption intensity per dollar of gross domestic product (GDP). If the United States had maintained a constant energy intensity of about 17,000 Btu (17.9 MJ) per dollar (2000) from 1975 to 2000, instead of decreasing intensity to about 10,000 Btu (10.6 MJ) per dollar, total consumption in 2000 would have been two-thirds higher: 165 quads (165 x 10^{15} Btu/year, or 174 EJ) rather than 99 quads (104 EJ) [1].

Thus, the United States saved about 66 quads (70 EJ) annually over that time through a combination of efficiency improvements, structural shifts toward less energy-intensive production (and off-shoring of energy-intense industry), and price-induced substitution or conservation. Note that energy prices decreased during this interval, so the price effect is likely small or negative.

Even if technical efficiency improvement accounted for only half of the energy intensity reduction from 1975 to 2000—a conservative assumption—this resource would still have provided about 33 quads (35 EJ) of primary energy by 2000, 50% more than all the coal or natural gas used that year, and more than four times the output of nuclear power.

U.S. energy intensity fell by about 2% per year between 1975 and 2000. Again, even if only half of this is attributed to efficiency improvement, the efficiency resource powered 1% annual economic growth with no emissions. In the last few years, as energy prices climbed and policy incentives for efficiency resumed after a lull in the 1990s, U.S. energy intensity fell by more than 2.6% per year.

Efficiency potential exists everywhere that energy is used, including buildings, vehicles, factories, and farms.

Resource Overview

Energy efficiency has the most potential and the greatest leverage when applied at the end-use stage of the energy chain. A technology as simple as a high-efficiency lamp, when used throughout the building sectors, can reduce the need for air-conditioning capacity and the power to supply it; diminish energy losses and defer capacity expansion in the power distribution system; and reduce fuel use, capacity expansion, and emission costs in power generation.

Efficiency opportunities are found everywhere energy is used. The key energy-using sectors and the corresponding efficiency opportunities include:

- **Buildings**. Building energy use accounts for about 40% of U.S. CO_2 emissions. Strategies for improving energy efficiency in buildings include efficient heating, cooling, lighting, and appliances; control systems that minimize heating and cooling loads and admit passive solar heat and natural daylight; and more energy-efficient building shells.

- **Vehicles**. Vehicle energy use accounts for more than 30% of U.S. CO_2 emissions. Strategies for improving energy efficiency in vehicles include designing and building more efficient cars, trucks, and aircraft (achieved through lightweight materials, improved aerodynamics, and efficient engines) and shifts in behavior that increase the use of public transit and other efficient forms of transport.

- **Industry**. Industry accounts for almost 30% of U.S. CO_2 emissions. Strategies for improving energy efficiency in industry include efficient motors and drive systems, reduced piping and pumping losses, heat recovery, cogeneration and industry-specific improvements in processes such as electrolysis.

Energy efficiency came to be seen as a resource in the 1970s. At that time, it became clear that U.S. oil production had peaked, domestic energy supplies could not keep up with unchecked demand, and the economic and environmental consequences of trying to do so would be unacceptable. Until then, efficiency had come about mostly through the natural progression of technological improvement and energy-using customers' response to energy prices.

Since then, a variety of mechanisms, including fiscal incentives, regulatory standards, utility programs, and other approaches have been used at the federal, state, and local levels to accelerate investment in energy efficiency (see **Accelerating Energy Efficiency Investments**, next page). After a lull in energy efficiency activity during the late 1990s, due in part to low oil prices and the focus on restructuring in the utility sector, many initiatives have begun recently in industry and at the state level. These include a revival of utility efficiency programs, such as a successful experiment in Vermont with a new type of "efficiency utility" that is dedicated solely to capturing savings from energy efficiency investments.

Accelerating Energy Efficiency Investments

Some of the mechanisms that have helped accelerate the adoption of energy efficiency strategies in the U.S. include [2]:

- **The Corporate Average Fuel Economy (CAFE) standards for cars and light trucks, which helped raise fleet efficiency by two-thirds from 1975 to 1990. After that, improvement stagnated as the industry focused on increasing power and weight.**
- **Electric and gas utility demand-side management (DSM) programs, in states where regulatory policy encouraged them, have achieved sufficient energy savings to cut their load growth estimates in half, and nationwide have avoided at least 30,000 megawatts (MW) of new supply capacity.**
- **Household appliance standards and "golden carrot" technology procurement programs have led to a 75% reduction in energy use in new refrigerators between 1975 and 2000, and significant improvements in water heaters, air conditioners, washer/dryers, etc. Building energy standards provide further savings.**
- **Industry partnership programs such as the U.S. Environmental Protection Agency's Energy Star programs have accelerated the transformation of product markets such as computer monitors to more efficient models.**

The introduction of hybrid vehicles and progress in reducing weight and aerodynamic drag in cars, trucks, and aircraft have stimulated new progress in vehicle efficiency, although the Federal CAFE standards have been strengthened only marginally. However, various states have taken the lead in innovation in energy efficiency policy. A 2002 California law that limits light vehicles' carbon dioxide emissions, and thus improves fuel economy, has since been endorsed by ten other states. Another approach, now in progress in Hawaii, Connecticut, and Washington, D.C., is revenue-neutral "feebates" to shift customer choice, within each vehicle-size class, by combining fees on purchases of inefficient vehicles with rebates on purchases of efficient vehicles.

Economics of Energy Efficiency

In order to compare the costs of efficiency measures and programs against supply side resources, one must take care to create truly comparable measures. One of the most common and useful measures is the cost of saved energy (CSE). The CSE is simply the levelized net cost of realizing the efficiency improvement divided by the annual savings in gigajoules (GJ), kilowatt-hours (kWh), million British thermal units (MBtu), etc. [3].

Determining the CSE provides a cost-effectiveness measure that can be compared to the cost of supply options. It is interesting to note the relationship between this measure and other common indicators of cost-effectiveness. For example, if the office lighting upgrade cited in **Calculating the Cost of Saved Energy** (this page) saves electricity that costs $0.08/kWh, or $800 annually, then the simple payback time, a common measure of project cost-effectiveness, is 2.5 years. Alternatively, the internal rate of return for the project is about 40%.

As this example illustrates, energy efficiency projects can yield very attractive returns. In spite of this—and the fact that the cost of saved energy is less than one-third the cost of supplied energy—energy consumers and firms routinely reject energy efficiency opportunities with a simple payback time of 2.5 years. This apparent distortion in the market for energy and energy services is one of the main reasons for policy mechanisms and utility investments to encourage efficient technology.

The emission savings from energy efficiency are similar to those of renewable energy. They simply represent the carbon content of the energy carrier that is avoided by using the efficient technology. The net cost of emission reductions from efficiency and renewable sources depends on the difference between these clean alternatives and the fossil energy supplies they replace. Because energy savings from efficiency programs often cost less than the supply resource they replace, the net cost of some of the resulting emission reductions can be negative.

Note that the cost of fossil energy replaced by efficiency and renewable sources—the so-called avoided cost—is not static. As more fossil energy is replaced by an increasing share of renewable sources, and especially by more energy efficiency, there is less demand for expensive sources. As a result, fossil energy prices fall, as they did in the late 1980s and 1990s. Compared to the lower avoided cost, the net cost of efficiency and renewable sources will appear higher.

Calculating the Cost of Saved Energy

Typically, the cost of energy efficiency is all or mostly an initial cost that comprises the increase in capital cost for the high-efficiency technology and the associated design, program, or administrative cost. In this case, CSE is:

CSE = Capital Cost * CRF / Annual Energy Savings

where CRF = Capital Recovery Factor, the ratio of a uniform annual (annuity) value and the present value of the annual stream, and it depends on the discount rate and the time horizon considered. In cases where annual non-energy operating costs increase or decrease significantly, this value would be added to, or subtracted from, the numerator.

For example, an office lighting upgrade with a net capital cost premium of $2,000 saves about 2 kW of power in a system that operates 5,000 hours per year. The annual energy saving is 10,000 kWh and, assuming a discount rate of 9% and 15-year time horizon (CRF = 0.125), the CSE is:

CSE = $2,000 * 0.125 / 10,000 = $0.025/kWh

Supply and CO_2 Reduction Curves

In utility resource planning, it is common practice to rank potential energy efficiency opportunities by their CSE in order to prioritize investments in efficiency programs and other resource options. Thus, the utilities that include a full range of DSM options in integrated resource planning (IRP) have produced cost curves of energy efficiency potential [4]. These cost curves look similar to supply curves and are sometimes referred to as "supply curves of saved energy."

A small number of utilities have produced such curves, and few have done so recently, so it is not possible to simply sum individual utility curves to reach a national-level curve. The best we can do is to examine estimates of energy efficiency potential and cost from specific utilities and then extrapolate roughly to the national scale.

Despite the incomplete nature of such information, it is still useful, because the resource planning process constrains the utility to report only the potential savings that it considers to be achievable, rather than raw technical-economic potential. If a utility plans for savings that cannot be realized, it runs a higher risk of inadequate supply capacity or reliability.

To create a national cost curve, we would ideally take a bottom-up approach, summing the individual cost curves from electric and gas utilities, and then adding efficiency potential that would be available in other sectors such as transport. However, even for utilities, such information is far from complete. Only a minority of electric utilities—and an even smaller share of gas utilities—has produced a comprehensive efficiency potential assessment, and many that have did not update the information after the wave of industry restructuring began in the 1990s.

Our approach here is to use a set of national assessments, which are highly simplified but reasonably complete, to estimate efficiency potential. For electricity, we rely on the so-called "five-labs study" from the Interlaboratory Working Group on Energy Efficient and Clean Energy Technologies. Their advanced scenario for 2020 provides a useful snapshot of efficiency potential after 20 years of strong policy and technical development [5]. Because little commitment was made in the five years after the study's publication, we take the results as an estimate of 2025 potential rather than 2020.

The five-labs study's electric-sector results include estimates of total technical-economic efficiency potential, which amount to about 1500 annual terawatt-hours (TWh) and 280 gigawatts (GW) of capacity at an average CSE of about $22/MWh. The total potential estimate is lowered by about 35% to reflect the share of total potential that is achievable given market and behavioral constraints, or about 980 annual TWh and 180 GW.

To create a cost curve, we take the average CSE, including an implementation cost of $6/MWh, and construct a linear cost curve from a net cost of zero up to a CSE value that is twice the average CSE. The result is shown in Figure 1.

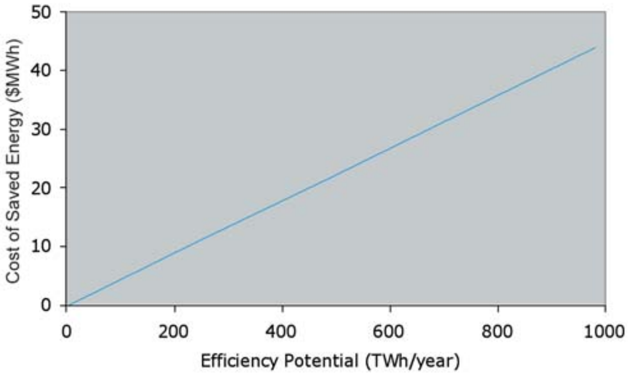

Figure 1. Electric efficiency cost curve (2025).

For estimates of 2025 natural gas and petroleum efficiency savings and costs, we rely on a more recent study on oil use conducted at Rocky Mountain Institute (RMI) [6]. We also adopt the assumptions used in the five-labs study regarding achievable efficiency potential (65% of technical-economic potential) and implementation potential ($0.6/MBtu).

The resulting efficiency cost curve is shown in Figure 2. Most of the natural gas savings are identified in industrial process heat and feedstocks and space and water heating in commercial and residential buildings. The electricity efficiency potential shown in Figure 1 is also found mostly in these sectors, although the most important end uses are industrial motor drives and air conditioning, lighting, and appliances in buildings. Because buildings are in use for 50 years or more, a significant share of the efficiency potential is based on retrofit measures to reduce heat flows through the building shell and resulting heating and cooling loads.

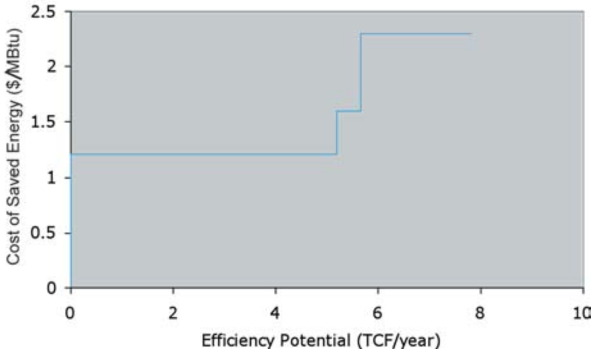

Figure 2. Natural gas efficiency cost curve (2025).

Efficiency potential for petroleum is identified in other sectors, mostly transportation and industrial feedstocks. The present debate on reducing oil use tends to emphasize alternative fuel options, such as ethanol, and new propulsion systems, such as hybrid motors and fuel cells. However, the RMI study shows that lightweight materials in cars and aircraft and advanced aerodynamics in trucks are the key to improving energy efficiency in cars, trucks, and aircraft.

The resulting oil efficiency cost curve, including the assumptions of implementation cost and achievable potential noted above, is shown in Figure 3.

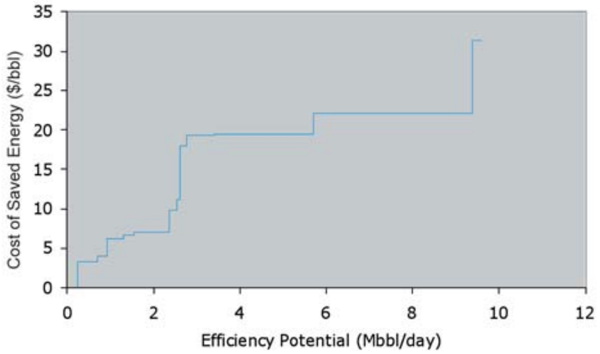

Figure 3. Petroleum efficiency cost curve (2025).

The cost estimates presented above are based on present technology costs. The reason to take a 20-year perspective in the analysis is that it takes time to implement efficiency programs, increase market penetration, and take advantage of the turnover and replacement of capital stock. We assumed no change in technology costs during that time.

This assumption is a compromise between two opposite perspectives. One holds that the efficiency resource is subject to the economic theory of diminishing returns and that, similar to a finite mineral resource, harnessing cost-effective opportunities leaves only less attractive ones for the future. Thus, once a significant part of the resource available at a given time is exploited, little potential remains at that cost level in the future—only more expensive options.

The other view recognizes that new technology and design knowledge continually create new efficiency opportunities and make existing ones less costly. Key technologies such as variable-speed motor drives and high efficiency lighting are now in Asian mass production and are cheaper and more effective than they were only a few years ago. Anecdotal evidence from reported CSE values in utility resource assessments seem to suggest that the latter view is the more correct one.

To create a cost curve for CO_2 emission reductions, we convert the energy savings values in each of the above efficiency potential estimates to primary energy equivalents in MBtu. We use these values to estimate costs in $/MBtu and emission reduction potential in metric tons of carbon (tC). Finally, we extrapolate the 2025 energy savings estimates to 2030 in proportion to estimated demand growth of 6% during the five-year interval.

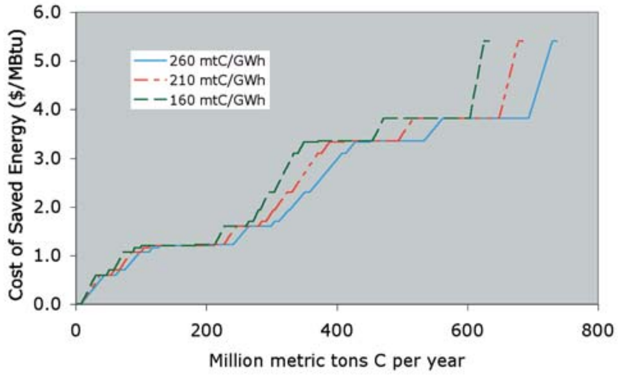

Figure 4. Carbon reduction cost curve based on energy efficiency potential by 2030.

We convert energy values to carbon equivalents based on the carbon content of the fuel. We assume that electricity has a carbon intensity ranging from 160 metric tons of carbon per gigawatt-hour (tC/GWh) to 260 tC/GWh. The latter value is effectively the intensity of a coal-fired steam plant. By comparison, a natural gas-fired combined-cycle plant has a carbon intensity of about 100 tC/GWh, and the average intensity of the national generation fleet is about 170 tC/GWh.

The resulting cost curve based on the combined energy efficiency potential for electricity, natural gas, and petroleum in 2030 is shown in Figure 4. The cost values are based on the primary energy equivalent of each energy carrier. In addition to technology costs and potential, each estimate includes assumptions about implementation costs and achievable potential consistent with the five-labs study.

Lightweight materials in cars and aircraft and advanced aerodynamics in trucks are the key to improving energy efficiency in transportation.

Conclusions

Assuming no change in carbon intensity of energy supply (i.e., before renewable energy supply is considered), the total achievable potential for cost-effective carbon emission reduction from energy efficiency in 2030 amounts to between 635 and 740 million metric tons of carbon per year (MtC/yr), depending on the assumed carbon intensity of electricity, or about 25% to 27% of baseline emissions. This is enough to essentially offset carbon emissions growth.

To achieve absolute reductions in emissions, intensity reductions are also required on the supply side, even if all the cost-effective potential identified above is captured. Renewable energy sources, biofuels, and possibly carbon sequestration provide a wide spectrum of options to reduce the carbon intensity of the energy supply system.

We can achieve reductions more quickly if energy efficiency improvements reduce the total energy demand that must be met by a mix of clean energy sources as well as conventional fossil fuels sources. In this way, energy efficiency and renewable sources are complementary parts of a comprehensive portfolio of CO_2 reduction strategies.

However, achieving a large part of the vast energy efficiency potential can also make it more difficult for renewable sources and other energy supply options to become competitive. Increasing efficiency reduces energy demand and has the potential to reduce prices of fossil fuels and other conventional energy sources, which is just what happened in the 1980s. While such price reductions would be good news for consumers, especially in fuel-importing developing countries such as China and India, their effect on renewable sources would be to make the marginal sources less competitive.

The most important uncertainties in this analysis are the assumptions regarding the share of efficiency potential that is achievable over time. This parameter depends on policy at the federal and state level, especially regarding utility regulation and incentives for fuel-efficient vehicles, as well as on the availability of information on efficiency options and on technical research and development. The realization of efficiency potential will increase where there is ongoing innovation to implement efficiency via mechanisms such as feebates, technology procurement, and new utility programs.

There is also uncertainty regarding the cost of energy-efficient technologies and the ultimate potential at a given cost, especially more than a few years in the future. As noted above, potential could decrease and costs increase with time as available potential is exhausted.

On the other hand, technological progress has provided a steady stream of cost reductions and new efficiency opportunities, which we expect to continue, making our estimates conservative. This view is supported by the American Institute of Architects, which recently adopted the “2030 Challenge” to make new buildings carbon neutral by 2030 [7]. Achieving such a goal would add to the efficiency potential estimated here, although it would not necessarily affect retrofit potential or performance of existing buildings.

Acknowledgements

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Tackling Climate Change in the U.S.

Potential Carbon Emissions Reductions in the Buildings Sector by 2030

by **Marilyn A. Brown, Ph.D.**
Therese K. Stovall and
Patrick J. Hughes, P.E.
Oak Ridge National Laboratory

Scott Milder, NREL PIX 10674

The Roy Lee Walker Elementary School in McKinney, Texas, incorporates a number of energy-efficient and renewable design features to help lower energy bills, including daylighting, rainwater collection, solar water heating, wind energy, and high efficiency lighting.

Approximately 43% of U.S. carbon dioxide (CO_2) emissions result from the energy services required by residential, commercial, and industrial buildings.

Approximately 43% of U.S. carbon dioxide (CO_2) emissions result from the energy services required by residential, commercial, and industrial buildings (Figure 1). When combined with other greenhouse gas (GHG) impacts of buildings—such as emissions from the manufacture of building materials and products, the transport of construction and demolition materials, and the passenger and freight transportation associated with urban sprawl—the result is an even larger GHG footprint.

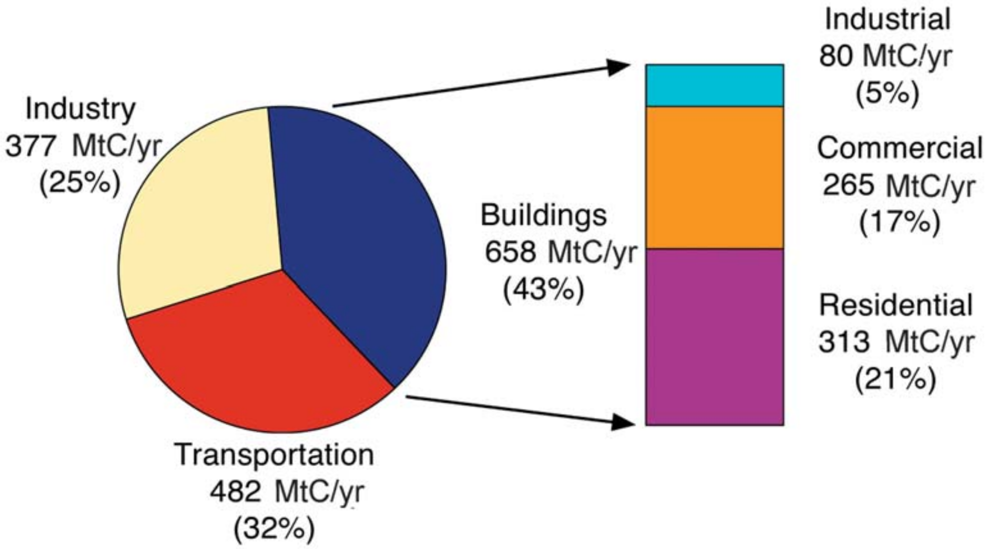

Figure 1. CO_2 emissions from fossil fuel combustion by end-use sector, 2002. (MtC/yr=million metric tons of carbon.)

Today and well into the future, many opportunities exist for curtailing GHG emissions from the U.S. building sector. Some of these opportunities require greater societal investment and costs. But others, particularly those focused on increased energy efficiency, could yield net savings by lowering energy bills, reducing operating and maintenance costs, and enhancing worker productivity and occupant comfort. Studies suggest that significant improvements in the energy efficiency of buildings appear to be cost-effective, but they are not likely to occur without extensive policy changes [1,2].

The vast majority of buildings that exist today will still exist in 2015, and at least half of the current stock will still be standing by mid-century. Thus, near-term policy interventions to significantly reduce GHG emissions quickly must generally target this market segment.

Nevertheless, advanced building designs and technologies are more easily introduced in the new construction market. While new buildings amount to only 2% to 3% of the existing building stock in any given year, advances in new construction can spill over into the broader replacement, retrofit, and renovation markets. As a result, transforming design and construction practices is critical to meeting long-term carbon reduction goals. In particular, significant energy savings can be achieved by building designs that respond to local climatic conditions, using as many passive systems as possible (e.g., passive solar heating, natural ventilation, daylighting, and shading) and other environmentally responsive features.

Opportunities in the Major Building Subsectors

Technology opportunities and building system innovations for reducing GHG emissions in homes and small businesses are similar. In both cases, the largest share of energy use serves space heating and cooling loads, which are principally a function of climatic conditions. In contrast, energy use in large commercial and industrial buildings is less climate sensitive due to relatively more building core versus perimeter, greater lighting and other internal loads, and diversity of type of business and occupancy. As a result, the following discussion of technology opportunities treats these two building subsectors separately.

Homes and Small Businesses

An energy-efficient building system must address two things—reduction of heat flow through the building envelope and improvement in the efficiency of all energy-consuming equipment and appliances. In the long run, integrated building systems in homes and small businesses have the potential of requiring net zero input of energy on an annual basis from the grid or other external sources through the incorporation of solar hot water, PV systems, and other on-site renewable energy technologies.

Building Envelope

The building envelope is the interface between the interior of a building and the outdoor environment. The envelope separates the living and working environment from the outside environment to provide protection from the elements and to control the transmission of cold, heat, moisture, and sunlight to maintain comfort for occupants. Energy pathways through the building envelope are traditionally divided into attic/roof, walls, windows, foundation, and air infiltration. Another important category of energy consumption is the embodied energy of the building envelope itself.

Components of the Building Envelope

Roof

The building's roof presents a large surface exposed to year-round direct sunlight. The heat available from this source is welcome during the winter, but summertime heat gains inflate air-conditioning loads. New reflective roof products address two shortcomings of current products. First, new pigmented roofing products reaching the market reflect far more of the incident thermal energy than traditional roofing. Early tests of these products in Miami show a cooling energy savings of 20% to 30%, with a simple payback of one to two years [3]. Second, research efforts are under way to develop "smart" roofing materials that absorb solar energy when the outdoor temperature is cool and reflect solar energy when the outdoor temperature is warm [4]. Because roof surfaces are replaced on regular, albeit long, intervals, these technology opportunities are pertinent for both new and existing buildings.

Wall Systems

Wall systems include framing elements and insulated cavities. In traditional wall designs, the framing portions of the wall are not insulated and represent a much greater portion of the total wall surface than is generally realized. New wall designs minimize heat loss by as much as 50% by reducing the amount of framing used and by optimizing the use of insulating materials [5]. These designs include optimal value engineering, structural insulated panels, and insulated concrete forms. Even with conventional wall design, minor modifications can significantly reduce energy transport. For example, polyurethane-bearing blocks have twice the insulating capability of wood and can be used to thermally isolate steel walls from foundations and from steel attic beams [6].

Improved wall system designs, however, generally apply only to new construction. The options for walls in existing buildings are more limited. Insulated sheathing is available for wall retrofits but often requires modifications to window jambs and doorframes. In the long term, the coatings under development for roofs could become a constituent of siding materials. Another approach is to take advantage of new insulating fabrics that could be hung from or applied to interior wall surfaces. The reflective properties of such materials can also be engineered to provide greater human comfort at reduced (winter) or elevated (summer) indoor temperatures, further increasing the energy savings [7].

Windows

Energy travels through windows via radiant energy, heat conduction through the frame, and air leakage around the window components. The higher-quality windows on the market today address all three of these energy paths, and they can be six times more energy-efficient than lower-quality windows [8]. A low-E coating on a window reduces the flow of infrared energy from the building to the environment, effectively increasing the window's R-value. Some of the low-E coatings are also designed to reject infrared energy from the sun, thus reducing air-conditioning loads. Electrochromic window coatings currently in the development stage offer dynamic control of spectral properties. For example, they can be controlled to reflect infrared energy during the summer but transmit this energy into the building during the heating season. Predicted HVAC energy savings for office buildings in arid climates using electrochromic windows range from 30% to 40% [9].

Air Infiltration

The twin goals of reducing energy use while controlling moisture levels can often be at odds. For example, in cold climates, a reduction in the infiltration of air into a building may also reduce a significant drying mechanism. Adding insulation inside a wall changes the temperature profile within the wall and so could create pockets of condensation that would not occur in a less energy-efficient wall. Faced with a choice between a less efficient but sound structure and a more efficient but rotting one, building managers will likely choose the former. However, current research efforts have advanced the understanding of heat, moisture, and air transport through building envelope systems, and envelopes that are durable and moisture-tolerant as well as energy-efficient can now be designed with confidence for different climates, thus removing this barrier to more efficient buildings [10].

Thermal Storage

One way to reduce energy consumption is to increase the thermal storage of the structure, especially in climates where daily temperature swings require both heating and cooling in the same 24-hour period. Massive construction materials, such as stone or adobe, have long been used for this purpose. However, lighter-weight thermal storage would be more attractive to consumers. In the near term, phase change materials (PCMs) can be used for thermal storage. In the long term, new solid-solid PCMs based on molecular design or nanocomposite materials will expand the thermal storage opportunities for building-integrated thermal storage [11]. Ideally, such materials will be incorporated as an integral element of existing building components (Figure 2). Annual heating and cooling savings estimates for simple residential buildings with PCM wallboard range from 15% to 20% [12].

Insulation

Vacuum insulation, while more expensive than other insulation products, offers 5 to 10 times the R-value for a given thickness of conventional insulation. It is therefore

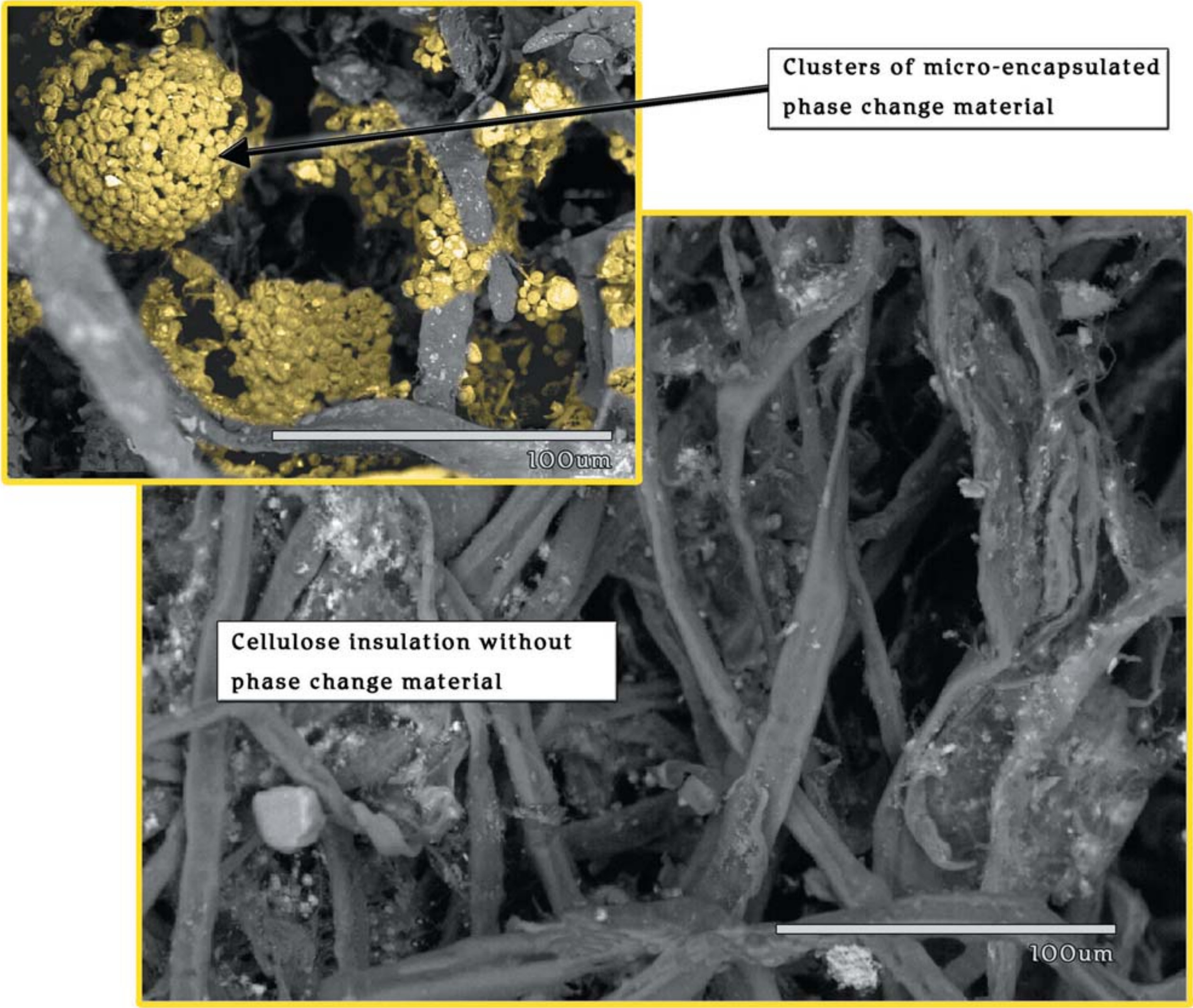

Figure 2. Micrographs showing inclusion of PCM microcapsules within cellulose insulation.

most likely to be used in confined spaces. It is already used in refrigerators and historic building renovations. These insulation panels could be used in exterior doors, ceilings, and floors in manufactured homes, floor heating systems, commercial building wall retrofits, and attic hatches and stairs [13].

Building Envelope Embodied Energy

The complexity of calculating embodied energy has given rise to a wide range of estimates. The Consortium for Research on Renewable Industrial Materials (CORRIM) was recently formed to examine the environmental and economic costs of building materials—from tree planting to building demolition [14]. Results show that the building's embodied energy equals about 8 to 10 times the annual energy used to heat and cool it and that the GHG emissions range from 21 to 47 metric tons over the life of a house. The best way to reduce this significant embodied energy in a building is to salvage and reuse materials from demolished buildings, even considering the extensive cleaning and repair often required of the salvage materials [15].

The building design, size, regional material sources, and framing material selection all greatly affect the embodied energy and GHG emissions. The CORRIM compared two house designs (wood framed versus concrete or steel framed) and found that for the same amount of living space, a wood frame house contains about 15% less embodied energy and emits about 30% less GHGs than does either a concrete frame or a metal frame house [16]. Other studies in this area have reached similar conclusions [17]. Nonetheless, optimizing the appropriate mix of low-GHG building materials will require project-specific analysis. For example, wood can store carbon that would otherwise have been emitted to the atmosphere. Concrete can reduce operating energy consumption by providing thermal mass to buffer temperature swings. Metal frames may contain up to 90% recycled material.

Energy-Consuming Equipment

Energy-consuming equipment in homes and small businesses includes systems such as HVAC, water heating, and lighting.

HVAC Systems

Many technical opportunities exist to save energy used in heating, ventilating, and air-conditioning (HVAC) systems. Smarter control systems could maximize the use of natural ventilation, especially if used with some form of thermal storage. Controlling relative humidity in air-conditioned spaces within the proper range would permit higher air temperatures while providing equal occupant comfort. Successful methods are already available to reduce the large (estimated in the 15% to 20% range) duct energy losses including aeroseal techniques [18]. Variable speed air handlers are also available to improve system efficiency and peformance [19]. In addition, ground-coupled heat pump systems can reduce whole-house energy consumption and peak demand by upwards of 30% and 40%, respectively [20]. In the long term, augmentation of ground heat exchangers with selective water sorbent technology offers the promise of meeting the performance of ground-coupled heat pumps at the cost of traditional systems [21].

Matching HVAC size to the building load has multiple implications for GHG emissions. Historically, contractors have considered it conservative to oversize HVAC installations, often using "rules of thumb" unrelated to any particular house design and especially inappropriate for the newer, more energy-efficient houses. Such oversizing causes units to cycle on and off more often, increasing thermal losses during each on/off transition. Frequent cycling also reduces occupant comfort, which in turn often leads occupants to adjust their thermostats to a value that increases total energy consumption. Therefore, downsizing HVAC equipment to match the reduced requirements of an energy-efficient building envelope can save investment dollars up front and can decrease energy consumption and GHG emissions as well.

Until recently, oil furnace efficiencies above the low- to mid-80s were rare. The availability of high-efficiency oil furnaces could significantly affect energy use through installation in new homes or as replacement units. One manufacturer has developed a condensing oil furnace with an Annual Fuel Use Efficiency (AFUE) rating of 95 that has overcome sooting problems prevalent with earlier versions of this technology [22].

Water Heating

Water heating is the second largest consumer of energy in homes behind space conditioning, accounting for 13% of total energy use. Given the current status of water-heater technology, water heaters offer a large potential for energy savings. Four technical improvements in water heating (heat pump water heaters, water heating dehumidifiers, heating water with waste heat, and solar water heaters) are described below. Other technology innovations include gas condensing water heaters and tankless (or instantaneous) water heaters, and these are considered by the U.S. Department of Energy (DOE) to be "promising technologies" for energy savings [23]. Another approach to reducing water heating energy is to improve the design of hot water distribution systems within buildings.

- The **heat pump water heater** (HPWH) moves heat from the house, garage, or crawlspace into the water tank—requiring less energy than would be needed to heat the water with an electric resistance water heater. An average HPWH uses less than 5 kilowatt-hours (kWh) of electrical energy to produce 64.3 gallons of hot water (the average daily hot water consumption for a typical U.S. household). A conventional water heater requires 13.3 kWh to accomplish the same task. As a side benefit, the HPWH can also provide cool, dehumidified air in the space where it is installed [24].

- The **water heating dehumidifier** combines the efficiency of a HPWH with dedicated dehumidification. Humidity control is a growing issue in housing, and an appliance that generates hot water at HPWH efficiencies and also operates as needed to control humidity may be valued in the marketplace.

- Multifunction integrated equipment offers the opportunity for a significant increase in efficiency through **heating water with waste heat**. For example, an integrated system that uses heat pumping to meet space heating, air conditioning, and water heating needs was recently demonstrated, with support from DOE, the Tennessee Valley Authority, and industrial partners [25]. A fully integrated heat pump prototype that modulates to satisfy heating, cooling, hot water, dehumidification, and ventilation needs is under development at Oak Ridge National Laboratory. The energy savings potential of the unit exceeds 50% compared to a baseline suite of appliances that would otherwise be required to meet all of these energy services, and over half of a home's electric load can be made demand-responsive with this one product.

- The **solar water heater** uses incident solar radiation to heat water for domestic uses. A reasonable estimate of the annual solar fraction of these systems (fraction supplied by solar with remainder supplied by the current energy source) is 0.5. In the residential building stock, if 50% of current electric water heaters and 20% of current gas water heaters were replaced with solar water heaters, the nation would annually save 0.3 quads of primary energy and reduce emissions by 6.7 million metric tons of carbon (MtC) per year [26].

Solar Photovoltaic (PV) Systems

Solar PV arrays are made from semiconducting devices that convert sunlight into electricity without producing air pollution or GHG emissions. A variety of PV system configurations are being used by electric utilities to provide "green power" to customers. Three types of systems are particularly relevant to buildings:

Stand-Alone Systems

Stand-alone PV systems produce power independently from the utility grid. In some off-the-grid locations, such systems can be more cost-effective than extending power lines. Many systems rely on battery storage that allows energy produced during the day to be used at night. Hybrid systems combine solar power with additional power sources such as wind or diesel. For most of the PV industry's history, stand-alone systems have dominated, but today grid-connected systems are moving to the forefront.

Grid-Connected Systems

Grid-connected PV systems supply surplus power back through the grid to the utility and take from the utility grid when the building system's power supply is low. These systems eliminate the need for storage, although arranging for the grid interconnection can be difficult. In many cases, utilities offer net metering, a simplified method of metering energy from renewable energy generators, such as a wind turbine. The excess electricity produced by the generating system spins the electricity meter backwards, effectively banking the electricity until it is needed and providing the customer with full retail value for all the electricity produced.

Building-Integrated Photovoltaic (BIPV) Systems

BIPV systems produce electricity and serve as construction materials at the same time. They can replace traditional building components, including curtain walls (for warming ventilation air), skylights, atrium roofs, awnings, roof tiles and shingles, and windows. They may be stand-alone or grid-connected systems.

Almost all locations in the United States have enough sunlight for PV systems, and these arrays can be easily sited on roofs, integrated into building components, or placed above parking lots. While integrating large quantities of solar PVs into the electricity grid is not simple due to its intermittence, the supply curve for PVs makes it a potentially valuable contributor to peak-shaving. (Peak-shaving involves reducing the amount of electricity drawn from the grid during utility-designated peak time periods, and optimal generation conditions for PV—hot, sunny weather—coincide with many utilities' peak loads.) In addition, distributed power offers the prospect of increased security and grid reliability [27].

Thin-film PV technology is the focus of current federal research and development (R&D) efforts because it holds considerable promise for cost reductions due to its need for less semiconductor material. In the long term, research into nanocomposites offers the promise of an inexpensive and high-efficiency solar energy conversion device [28].

Integrated Building Systems

By 2010, advances in building envelopes, equipment, and whole-building integration may lead to 50% reductions in the energy requirements of new buildings relative to 2000. Incremental capital cost estimates for these advanced building systems run from 0% to 2% of the total building cost, because cost savings on the downsized HVAC system offset most of the additional building envelope cost [29]. If augmented by on-site power, buildings could reduce their net energy requirements by perhaps 75% by 2015. A few large prototype homes incorporating such technology have been constructed with incremental costs of only 5% to 7%, which are generally recovered from reduced energy bills in fewer than five years [30]. PVs offer the possibility of "net-zero-energy" buildings, when combined with 60% to 70% whole building energy reductions. This goal may be achievable as a cost-competitive housing alternative by 2020 (see Figure 3).

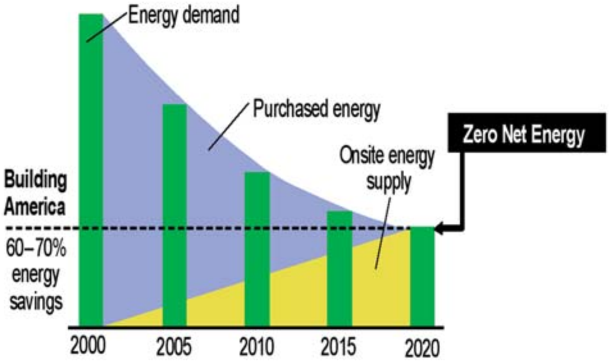

Figure 3. The pathway to net zero energy homes [31].

Large Commercial and Industrial Buildings

Efficient lighting and distributed energy technologies hold great promise in large commercial and industrial buildings. Many of the technologies described in the previous section have significant application potential in larger buildings, and current research holds the promise for improved wireless sensor technologies, along with advances in control technologies such as neural networks and adaptive controls. In the long term, these components will be combined into robust building management systems. Unlike today's simple thermostats and timers, these sophisticated systems will enable true optimization of building energy services, both reducing energy use and improving conditions for the building occupants [32].

Lighting

Current lighting technologies are expected to benefit from incremental improvements over the next 20 years, and two areas of research (hybrid solar lighting and solid-state lighting) should be able to deliver even greater savings. The efficiency of fluorescent lighting used in many larger commercial and industrial buildings is expected to improve by about 10% by 2025 [33]. This improvement, when combined with more adaptive lighting arrangements, could increase savings by about another 15% to 20%.

One alternative lighting system for commercial buildings is called hybrid solar lighting. In this system, a roof-mounted tracking dish solar collector sends the visible portion of solar energy into light-conducting optical cables, where it is piped to interior building spaces. Controllers supplement this light as necessary with fluorescent lights to provide the desired illumination levels at each location. Early experiments show that hybrid lighting is a viable option for lighting on the top two floors of most commercial buildings. It would, therefore, be applicable to roughly two-thirds of the commercial floor space in the United States. In retrofit markets, hybrid lighting can be more readily incorporated than skylights into existing building designs, and unlike skylights, the flexible optical fibers can be rerouted to different locations during renovations. If cost reduction targets are met, this technology is estimated to have a payback period of fewer than five years for some applications [34].

For the long term, research into solid-state lighting shows great promise. Preliminary roadmaps estimate that cumulative savings by 2020 could amount to 16.6 quads of electrical energy and 258 MtC, or 0.2%, of the projected total U.S. carbon emissions over that time period [35]. Today's light emitting diodes (LEDs) produce light at an efficiency only slightly higher than standard incandescent lights and are already used for specialty applications such as traffic lights and exit signs. Technology improvements are expected to bring brighter LEDs that provide light equivalent to existing fluorescent fixtures with 25% to 45% less electricity usage. With successful R&D in these products, energy savings over all sectors could be as high as 3 to 4 quads, or 60 to 75 MtC, in 2025 [36]. Global use of this technology is projected to save 1,100 billion kWh/yr, corresponding to reduced carbon emissions of roughly 200 MtC [37].

Climate-Friendly Distributed Energy

Distributed energy resources are small-power generation or storage systems located close to the point of use. Not all distributed energy is climate-friendly, a case in point being diesel-generator sets. But other distributed generation technologies offer significant potential for reduced emissions of CO_2 and local air pollutants, partly because of their higher efficiencies through cogeneration and partly because of their use of on-site renewable resources and low-GHG fuels such as natural gas. Other advantages include fuel flexibility, reduced transmission and distribution line losses, enhanced power quality and reliability, more end-user control, and deferral of investments and siting controversies associated with power generation, transmission, and distribution expansions. Many experts believe that these potential advantages will bring about a "paradigm shift" in the energy industry, away from central power generation to distributed generation (Figure 4).

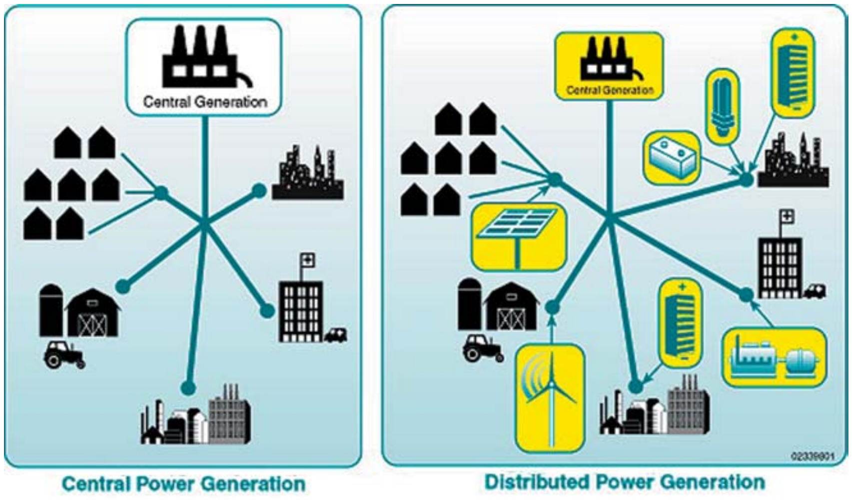

Figure 4. The transition to distributed energy resources.

Some distributed generation technologies, like PVs and fuel cells, can generate electricity with no emissions or with at least fewer emissions than central station fossil fuel-fired power plants. Total emissions can also be reduced through distributed generation using industrial turbines (up to 20 MW), fuel cells, microturbines, and internal combustion engines, if the waste heat generated is usefully employed on site to improve overall system efficiency. Based on the remaining technical potential for cogeneration in the industrial sector alone, it is estimated that nearly 1 quad of primary energy could be saved in the year 2025 [38]. Packaged cogeneration units that include cooling capabilities (and are therefore more attractive to commercial building operators) are projected to save 0.3 quads in 2025 [39].

Today's distributed generation market in the United States is dominated by backup generation. Customers include hospitals, industrial plants, Internet server hubs, and other businesses that have high costs associated with power outages. Markets are likely to grow as wealth increases and more consumers are willing to pay to avoid the inconvenience of blackouts. Smaller niche markets are growing where distributed energy resources are used as a stand-alone power source for remote sites, as a cost reducer associated with on-peak electricity charges and price spikes, and as a way to take advantage of cogeneration efficiencies. Distributed generation could be particularly advantageous in newly settled areas by requiring less infrastructure investment, and by being more responsive to rapidly growing demand for power. Increased demand will likely continue and possibly accelerate well into the future as small-scale modular units improve in performance; as cost, interconnection, backup, and other barriers are tackled; as the demand for electricity continues to grow; and as the worldwide digital economy expands. Over the next half-century, it is possible that the demand for ultra-reliable power service will increase far more rapidly than the demand for electricity itself. Efficient forms of distributed energy resources could meet this demand.

For distributed generation to enhance system-level efficiency, improvements will be required in the performance of power-producing equipment, including advanced sensors and controls as well as a next generation of power electronics, energy storage, and heat exchangers to improve waste heat recovery and cycle efficiencies. With successful research, development, and demonstration (RD&D), the United States (and much of the rest of the world) could realize a paradigm shift to ultra-high-efficiency, ultra-low-emission, fuel-flexible, and cost-competitive distributed generation technologies integrated into buildings. These technologies would be interconnected with the nation's energy infrastructure and operated in an optimized manner to maximize value to users and energy suppliers while protecting the environment. Broadly deployed, these technologies could potentially meet future energy services needs in large buildings, while reducing the total societal investments to do so, when infrastructure and end-use investments are considered together.

Building-Specific Policy Options

The mosaic of current policies affecting the building sector is complex and dynamic, ranging from local, state, and regional initiatives to a portfolio of federal policies and programs. Various taxonomies have been used to describe policy instruments. Typically these distinguish between regulations, financial incentives, information and education, management of government energy use, and subsidies for R&D. Seven specific policies are described below—six market transformation policies plus R&D. Each of these has been evaluated enough that estimating potential future impacts is viable.

- **Building Codes**. The greatest opportunity to make buildings more efficient is during the construction phase. Many efficiency options are lost if they are not built into the original design. By requiring new buildings to achieve at least a minimum level of energy efficiency, building codes reduce these lost opportunities.

- **Appliance and Equipment Efficiency Standards**. Appliance and equipment standards require minimum efficiencies to be met by all regulated products sold, thereby eliminating the least efficient products from the market.

- **Utility-Based Financial Incentive Programs**. Utility-based financial incentive programs have been in operation since the early 1980s, when it became clear that information and education alone produced only limited energy and demand savings. By reducing demand, energy efficiency is a low-cost contributor to system adequacy—the ability of the electric system to supply the aggregate energy demand at all times—because it reduces the base load as well as the peak power demand.

- **Low-Income Weatherization Assistance**. Residences occupied by low-income citizens tend to be among the least energy-efficient in the housing stock. The DOE's Weatherization Assistance Program has served as the nation's core program for delivering energy conservation services to low-income Americans since it was created in 1976.

- **ENERGY STAR® Program**. The ENERGY STAR program was introduced by EPA in 1992 to fill the information gap that hinders market penetration of energy-efficient products and practices. Its market-based approach involves four parts: (1) using the ENERGY STAR label to clearly identify which products, practices, new homes, and buildings are energy-efficient; (2) empowering decision-makers by providing energy performance assessment tools and project guidelines for efficiency improvements; (3) helping retail and service companies in the delivery chain to easily offer energy-efficient products and services; and (4) partnering with other energy-efficiency programs to leverage national resources and maximize impacts.

- **Federal Energy Management Program**. Chartered in 1973, the Federal Energy Management Program (FEMP) seeks to reduce the cost and environmental impact of the federal government by advancing energy efficiency and water conservation, promoting the use of distributed and renewable energy, and improving utility management decisions at federal sites. Congress and the president impose energy use reduction and renewable energy goals on all federal agencies, and FEMP provides specialized tools and assistance to help agencies meet their goals.

- **Federal Funding for Building Technologies R&D**. In the long run, opportunities for a low-GHG energy future depend critically on new and emerging technologies. Federal support for R&D in this highly fragmented and competitive sector of the economy is essential to keep the pipeline of new and emerging technologies full. Without R&D, the pipeline runs dry and the six market transformation policies cannot sustain their savings levels.

Summing the estimates of energy and carbon emission reductions for these seven policies provides a reasonable estimate of the benefits that could be achieved by extending and expanding them into the future (Table 1). While summing these estimates does involve some amount of double-counting, additional funding could substantially increase the impacts of many of these programs, causing total savings to be greater.

TABLE 1:
Prospective U.S. energy savings and carbon emission reductions from selected policies.

	Prospective annual primary energy savings, in quads (period)	Prospective annual carbon emission savings, in MtC
Building codes	0.26 (2016)	6.0
Appliance and equipment efficiency standards	5.27 (2020)	88.0
Utility-based financial incentive programs	0.63 (2020)	10.2
Low-income weatherization assistance	0.06 (2020)	0.5
ENERGY STAR® Program	1.08 (2020)	21.5
Federal Energy Management Program	0.07 (2020)	1.1
Federal funding for buildings energy R&D	4.20 (2025)	71.0
Total	**11.60 (variable)**	**198.0**

Note: Sources for all numbers are provided in Brown, et al. (2005), along with the underlying assumptions [40].

With these caveats in mind, potential annual impacts in the 2020 to 2025 time frame are 11.6 quads saved and 198 MtC avoided, representing 23% of the forecasted energy consumption and carbon emissions of buildings in the United States in 2025. The largest contributors to these savings are federal funding for buildings energy R&D and appliance standards.

This prospective energy savings estimate is larger than the results derived from an advanced policy case modeled over a 25-year period in the *Scenarios for a Clean Energy Future* (that estimate was 8 quads for the building sector) [41]. However, the carbon reductions (238 MtC) are similar in magnitude. The 25-year study did not model as large a potential impact for research-driven technology breakthroughs in the building sector, which accounts for its smaller energy savings estimates, but it did model a significant decarbonization of the power sector associated with the advanced policies, which accounts for its comparable carbon reduction estimates.

Figure 5 compares the scenario described in a report published by the Pew Center on Global Climate Change (on which this paper is largely based) with the DOE's Energy Information Administration's (EIA's) "Reference Case Forecast" and its "High Economic Growth" scenario for the building sector. The reference case assumes that R&D spending and market transformation programs continue at today's pace. The high economic growth scenario assumes a faster rate of GDP growth and hence greater carbon dioxide emissions. In contrast, the seven buildings-related policies examined here (R&D plus six market transformation policies) bring carbon emissions in 2025 almost back to 2004 levels by nearly offsetting the projected 2004-2025 increase of 14 quads (Figure 6).

Similarly, the seven policies could potentially reduce the forecasted CO_2 growth from buildings to less than 7% between 2002 and 2025 (from a forecasted increase of 250 MtC to an increase of only 40 MtC). At the same time, the built environment in 2025 will be meeting the needs of an economy that will have grown by 96% [42]. After 2025, the nation could begin to achieve the much deeper reductions that many believe are needed to mitigate climate change.

Market transformation and R&D go hand-in-hand. Without R&D to keep the pipeline full, the market transformation programs cannot sustain their savings. At the same time, while R&D can lead to savings whether or not market transformation programs exist, the latter accelerates and expands the reach of the impacts.

The methodology used for estimating the savings impacts of R&D required the selection of specific technologies. However, it should be noted that R&D is managed as a portfolio, the successful pathways are unknown in advance, and the savings yield from a given R&D investment level has far more relevance than the attribution to specific technologies in Figure 6. Similar estimated energy savings could result from many alternate technology R&D portfolios with a similar R&D investment level.

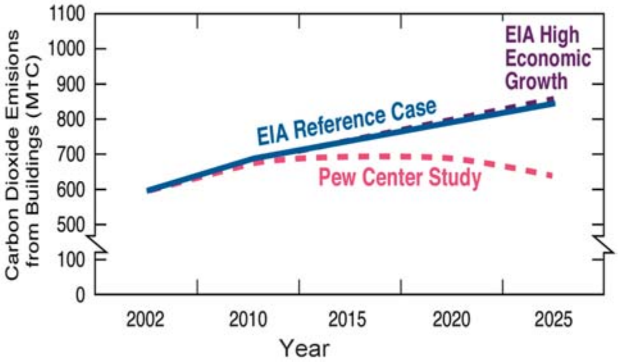

Figure 5. Scenarios of U.S. energy use and carbon emissions in the buildings sector: 2002 to 2025.

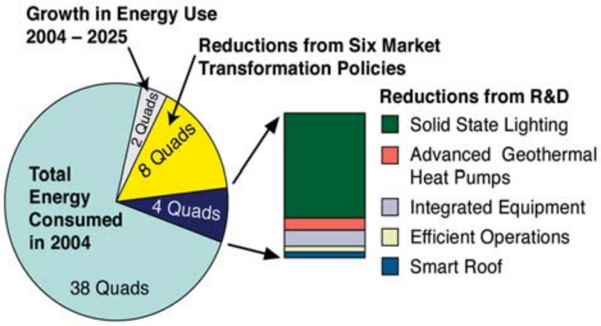

Figure 6. 52 quads building sector energy use in 2025 based on the Pew Center Scenario.

Conclusions

Homes, offices, and industrial buildings rarely incorporate the full complement of cost-effective climate-friendly technologies and smart growth, despite the sizeable costs that inefficient and environmentally insensitive designs impose on consumers and the nation. To significantly reduce GHG emissions from the building sector, an integrated approach is needed—one that coordinates across technical and policy solutions, integrates engineering approaches with architectural design, considers design decisions within the realities of building operation, integrates green building with smart-growth concepts, and takes into account the timing of policy impacts and technology advances.

Acknowledgements

This paper is based largely on a report published by the Pew Center on Global Climate Change that describes the potential for greenhouse gas (GHG) reductions from the buildings sector [42].

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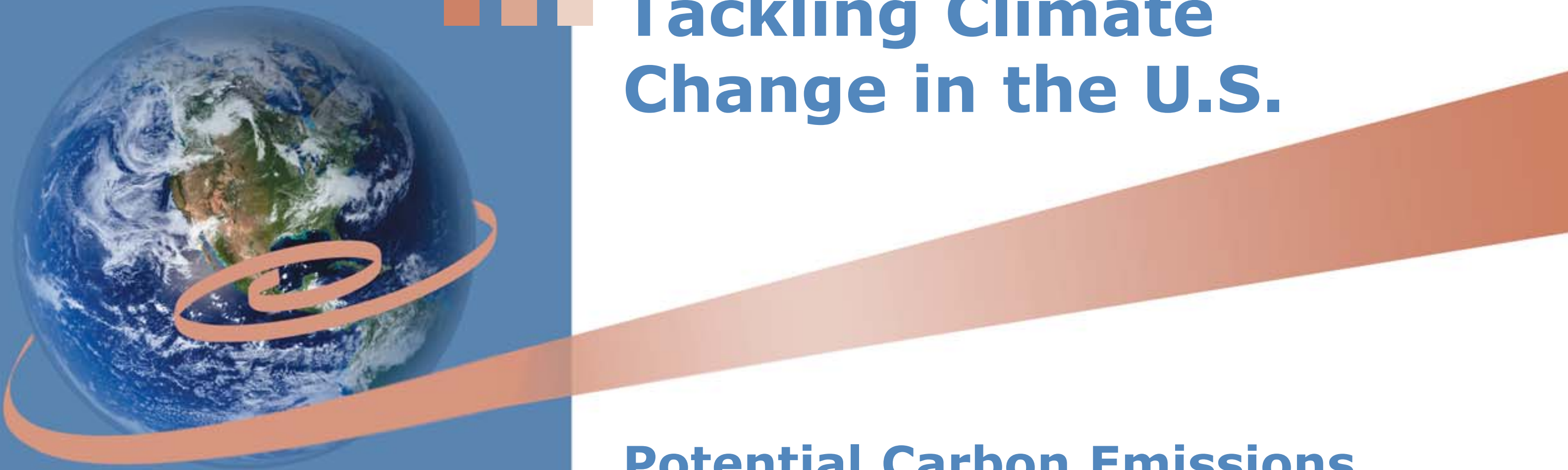

Tackling Climate Change in the U.S.

Potential Carbon Emissions Reductions from Plug-in Hybrid Electric Vehicles by 2030

by **Peter Lilienthal, Ph.D.** and
Howard Brown
National Renewable Energy Laboratory

Keith Wipke, NREL PIX 14731

This Toyota Prius has been converted into a plug-in hybrid electric vehicle so that its electric battery can be recharged by plugging its cord into a standard 110-volt outlet. A computer inside the vehicle determines when it is most efficient for the vehicle to be fueled by electricity or by liquid fuel (either petroleum or biofuels).

The additional wind generation enabled by the PHEVs distributed storage would provide all the electricity needed by the PHEV fleet, and also some of the electricity needed for normal demand.

The transportation sector is responsible for 33% of total U.S. carbon dioxide emissions. Gasoline, mostly for light duty vehicles, represents 60% of U.S. transportation emissions or 20% of total U.S. emissions.[1]

There are many ways to reduce petroleum consumption and carbon emissions in the transportation sector, including more efficient powertrains and a variety of biofuels. Hybrid vehicles are a promising technology for improving vehicle efficiency and reducing carbon emissions. The standard hybrid vehicle, which is becoming increasingly popular, reduces carbon emissions by increasing fuel efficiency. This paper focuses on plug-in hybrid electric vehicle technology, which adds additional battery capacity and charging capability to current hybrid electric vehicle technology. Plug-in vehicles thereby make possible substantial vehicle operation on energy derived from the electrical grid rather than from gasoline.

Of primary importance, such electrical operation would clearly help reduce dependence on imported oil. Also, consumers would pay more for the extra battery capacity but, as described below, enjoy greatly reduced operating cost, paying only about a quarter as much for mileage driven on electric power alone. But what would the impact be on carbon emissions? On the one hand, because electric motors are more efficient than internal combustion engines, you would expect net emission reduction. On the other hand, much of our electricity is produced from coal, which has a higher carbon-to-energy ratio than petroleum. Modeling for carbon dioxide impacts provides both a general assessment of the tradeoff between these short-term effects and insight into more complex interaction with the utility sector in the long term.

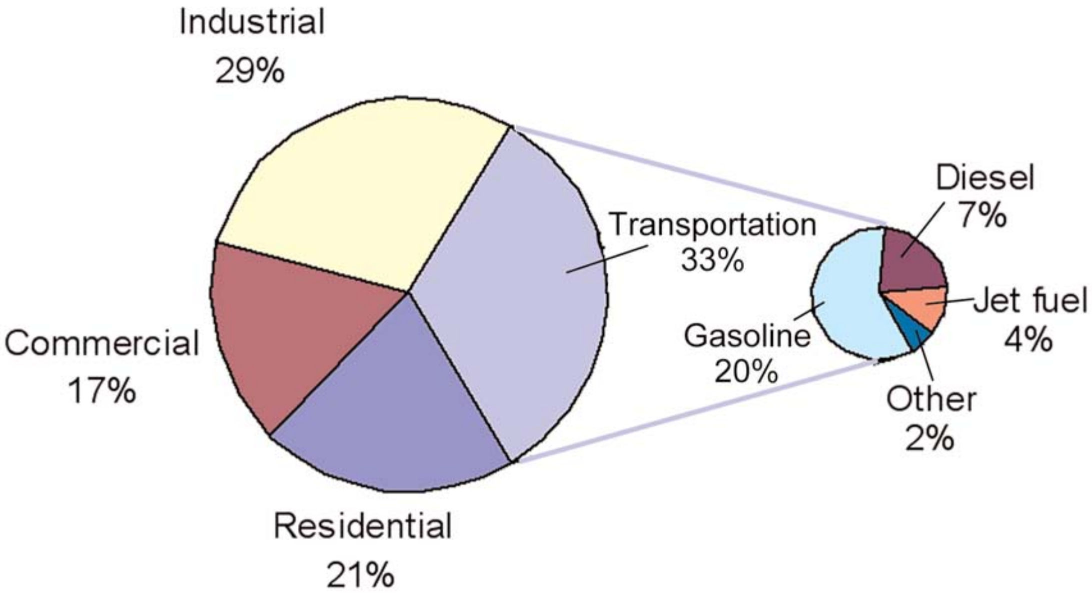

Figure 1. U.S. CO_2 emissions (2004)

Technology Overview

The current generation of hybrid vehicles has a small battery (~1 kilowatt-hour [kWh]) that improves the vehicle's efficiency in three ways. First, the gasoline engine can be sized slightly smaller—and therefore operate in a more efficient range without sacrificing performance because the electric motor can supplement the engine when needed. Second, the gasoline engine can be shut down during periods when it would be operating inefficiently, particularly idling at stops, but also at slow speeds. Finally, it enables regenerative braking whereby some of the vehicle's kinetic energy is converted into electricity by the electric motor acting as a generator and charging the battery.

Plug-in hybrid vehicles (PHEVS) are similar to hybrid vehicles with two exceptions. First, the small battery is replaced with a larger battery pack. PHEVs are classified by the number of miles they could theoretically operate in an all-electric mode. A PHEV-10 would have a battery large enough to theoretically go 10 miles per charge. However, there are substantial advantages to a hybrid dispatch strategy whereby a PHEV uses both electric and conventional drive, depending on instantaneous power requirements and not just the battery state of charge.

Second, the vehicle can be plugged into a standard low-voltage home, office, or garage outlet to charge the battery without the engine running. The vehicles have onboard controls to use the appropriate power source for maximum efficiency. In a typical drive cycle, the battery would start full and gradually deplete its charge, eventually operating like today's conventional hybrids.

Because 50% of all U.S. vehicles travel less than 20 miles per day,[2] even PHEVs with modest battery packs could run primarily on the electric motor with stored energy for much of a typical day's driving, thereby dramatically reducing liquid fuel use. The biggest challenge plug-in hybrids inherit from electric vehicles is the cost of batteries. Unlike a pure electric vehicle, the plug-in has a smaller battery pack and the range and refueling options of a conventional car. There are many enhancements to battery technology being researched around the world. At the National Renewable Energy Laboratory (NREL), researchers are extensively exploring thermal management, modeling, and systems solutions to improve energy storage technology. Even at today's battery costs, however, the lower operating cost of plug-ins could be very attractive. At $2.77/gallon (September 2005) and 21 miles per gallon for gasoline and $0.08/kilowatt-hour (January 2006) and 2.8 miles/kilowatt-hour for electricity,[3] electric motor "fuel" costs are only about three cents per mile for miles driven on the electric motor alone, compared to about 13 cents per mile for a gasoline engine. Because most PHEV operation would use both the electric motor and the gasoline engine, the net cost would be 6 to 8 cents per mile, still cutting costs in half.

> *Electric motor "fuel" costs are only about three cents per mile for miles driven on the electric motor alone, compared to about 13 cents per mile for a gasoline engine.*

Potential Carbon Emissions Reductions

PHEVs would drastically reduce operating cost per mile and dependence on petroleum, but what would the impact of their use of electrical power rather than gasoline or diesel be on greenhouse gas emissions? The impact would likely not be as dramatic, because about 52% of U.S. electrical generation currently comes from coal,[4] which has very high carbon emissions with today's technology. As the table below shows, PHEV operation on electricity generated by base-load coal plants would modestly decrease carbon dioxide generation versus gasoline engine operation (imported fuel and operating cost reduction benefits would still accrue). For more efficient power generation such as gas-fired combined-cycle plants, however, there would be quite substantial reduction in carbon dioxide emissions. (Nuclear, hydroelectric, and wind and other renewable electric generation approach 100% reduction.)

Table 1:
Using emissions data from the Environmental Protection Agency's Emissions & Generation Resource Integrated Database (eGRID) [1], we calculated carbon emission reductions for driving a PHEV on electrical power rather than gasoline.

Technology	**Carbon***	
	Per Gallon	**Per Mile**
Gasoline Engine	6.6 lb.	.22 lb.
PHEV/Modern Coal-Fired Power Plant	5.6 lb.	.19 lb.
PHEV/Gas Combined-Cycle Power Plant	2.5 lb.	.08 lb.

*Assumes 10 kWh of electricity is required to drive the same distance (30 miles) as on one gallon of gasoline; includes 10% transmission loss.

Using eGRID, we calculated carbon dioxide emission reduction of 42% per mile driven on electrical power on a national average. As the following map shows, however, the extent of reduction varies widely from 0% in North Dakota, which relies mostly on low-Btu lignite coal, to more than an 80% reduction in Pacific Northwest states that use large amounts of hydroelectric power.

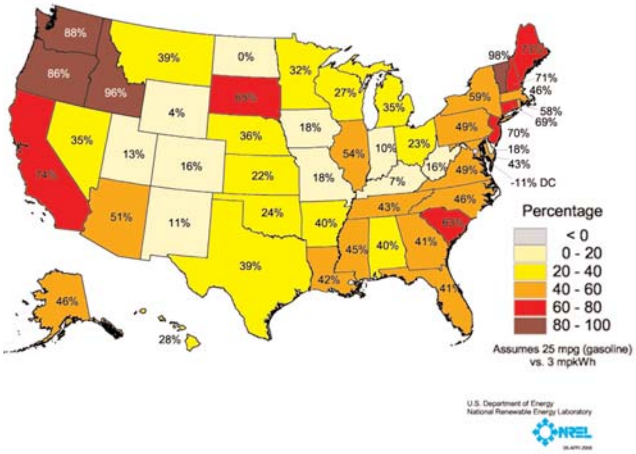

Figure 2. National average carbon savings from EVs or PHEVs is 42%.

Nonetheless, the map shows that use of plug-ins would provide carbon emissions reductions in 49 states, including some that are heavily dependent on coal-fired generation.

These numbers are per mile driven electrically based upon current (2000) total electrical generation patterns. A more accurate analysis would need to look at the marginal generation on-line during periods when the vehicles are being charged. This would require more data on utility operations than was available for this study. It also requires assumptions about PHEV charging strategy and the mix of future utility generation.

The actual emission reductions that are obtained by switching from gasoline to electricity will depend on the extent of market penetration. They will also depend on the motor-versus-engine control strategy design of the vehicle and assumptions about driving and charging behavior. Data for the map were calculated by assuming that the vehicle gets 3 miles per kWh in electric mode and 25 miles per gallon in gasoline mode. In reality, a plug-in hybrid would use a blended control strategy, so the impacts would depend on daily driving patterns. Centralizing primary transportation energy generation could also facilitate use of carbon sequestration technology to reduce greenhouse gas impacts.

Impact on the Electrical Grid

At initial levels of market penetration, PHEVs would have a negligible effect on the utility sector. One million PHEVs charging simultaneously at the rate of 1.5 kW would use approximately 0.16% of the total U.S. generating capacity. At higher levels of penetration, PHEV technology could have a significantly positive impact on the way the electrical grid operates. If the charging of PHEVs occurred primarily off-peak, they could improve the load curve for electric utilities. An NREL research project is studying PHEV charging patterns under various utility constraints. This project has found that, depending on battery capacity, gasoline consumption per vehicle could be reduced 45% to 70% even when charging was limited to off-peak nighttime power [2].

Just as plug-ins seem a logical next step for hybrid-electric vehicles, making the plug-in bi-directional so that homes or utilities could draw power back from the plug-in batteries when needed is a natural step beyond that. Such "vehicle-to-grid" or "V2G" systems will allow homeowners or utilities to take greater advantage of the investment in vehicle batteries, thereby reducing vehicle owner cost.

One scenario has vehicle owners avoiding peak time charges by drawing on their own electrical storage system at peak times (while recharging at low-rate off-peak times). Another has utilities paying the vehicle owners for the storage capacity. Either way, V2G batteries become distributed storage systems for the electrical grid and would help pay back the cost of having these added batteries in PHEVs.

Commercially available storage technologies include pumped hydro, compressed air, and stationary batteries. These technologies are restricted by high costs, but also by their singular use in the electric power sector. Energy storage in V2G PHEVs offers a significant advantage—vehicle batteries would provide services to both the electric sector and the transportation sector, increasing their utilization and cost effectiveness.

The distributed storage would also make the electric grid more stable, secure, and resilient by providing services such as frequency regulation and spinning reserve as well as backup capacity within the distribution system. For example, commuters could be paid to plug their vehicles in while at work to ensure their employers have high-quality power throughout the day. Currently, altering the operation of conventional generation resources provides these services, a practice that reduces efficiency and increases emissions.

Utility base load power generators produce electricity at a relatively low per-unit cost, but their quick-response electricity generation is generally much more expensive. Services such as spinning reserves and regulation cost $12 billion per year in the United States, 5% of total electricity costs. Researchers calculated that the value of these quick-response services to utilities might be sufficient to compensate car owners as much as $2,000 to $3,000 per year to "borrow" energy storage capacity. Much of that value can be derived from capacity payments because utilities must assure that they have reserve capacity even if it is not used. Electricity should only be discharged from the vehicle when its value is high enough to cover the incremental wear on the battery. Passing through such savings could dramatically reduce the incremental cost of plug-in hybrids versus conventional vehicles [3].

In addition to allowing conventional resources to operate more efficiently, distributed electrical storage provided by V2G systems could allow greater penetration of wind and solar resources. Because the resource base for wind and solar is many times the current installed generation capacity, there is considerable interest in increasing the penetration of these intermittent renewable energy sources. Large-scale energy storage—such as extensive market penetration of V2G PHEVs could provide—would significantly increase the potential market penetration of intermittent sources on the grid. Energy storage would serve two purposes. First it would absorb excess generation during times of high wind or solar output, particularly at times of low natural demand. Second, energy storage would discharge during times of low solar or wind output, providing “firm” capacity and reducing the need for conventional generation capacity. Altogether the electric system would have a higher capacity factor with a more secure and level load.

Another NREL research project uses our Wind Deployment System (WinDS) Model to project the potential increase in wind-powered electrical generation from PHEV use. The preliminary analysis assumed that 50% of the vehicle fleet in 2050 would consist of PHEV-60s. In that scenario WindDS projected that the PHEVs would enable the cost-effective quantity of wind capacity in 2050 to more than double from 208 gigawatts (GW) to 443 GW. This increase in wind penetration causes the total carbon emissions of the utility sector to decrease from 1,984 million tons per year to 1,969 million tons, even with the increased load from charging PHEVs.

The combined impact from the transportation and utility sectors would reduce carbon emissions by 170 million metric tons per year (MtC/yr), assuming a 35-mpg base-case fleet, or 284 MtC/yr, assuming a 22-mpg base fleet [4]. In this scenario, the additional wind generation enabled by the PHEVs distributed storage would provide all the electricity needed by the PHEV fleet, and also some of the electricity needed for normal demand.

More work is needed to examine the benefits of PHEVs to renewable energy that looks at specific integration issues. Solar and wind energy have variable resource availability that can challenge conventional utility systems’ ability to adjust their output. There is general consensus that 10% to 50% of the capacity of a utility system can come from variable sources such as wind and solar. Transmission and resource variability issues currently become problematic at the upper end of that range, but distributed storage from PHEVs can help with these issues.

The distributed storage would also make the electric grid more stable, secure, and resilient.

Conclusions

Plug-in hybrid vehicles have the potential to provide a wide range of benefits. The most dramatic benefit is a reduction in petroleum consumption, but they also enable significant reductions in carbon emissions. Even though the current mix of electric generation in the United States gets the majority of its electricity from coal, PHEVs emit substantially less carbon than conventional vehicles because of the increased efficiency of electric drive. They can increase the adoption of renewable energy in the electric utility sector, and they can make the nation's electric system more stable, secure, and resilient.

Acknowledgements

The authors gratefully acknowledge contributions and advice from colleagues Paul Denholm, Anthony Markel, Terry Penney, Walter Short, and Andrew Simpson.

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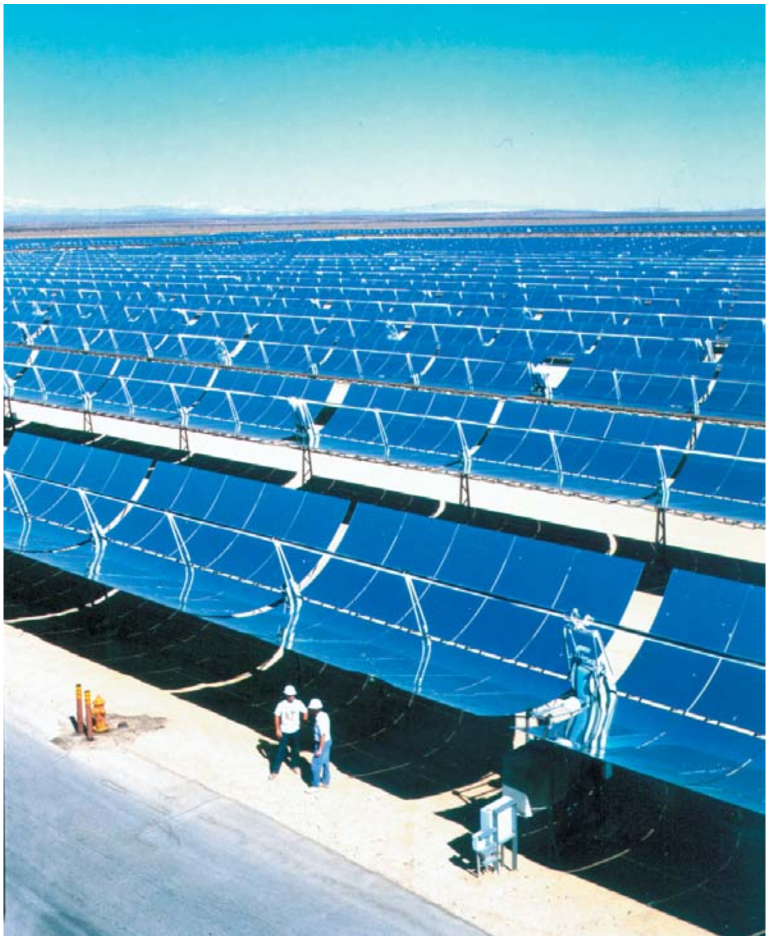
Tackling Climate Change in the U.S.

Potential Carbon Emissions Reductions from Concentrating Solar Power by 2030

by **Mark S. Mehos**
National Renewable Energy Laboratory and
David W. Kearney, Ph.D.
Kearney and Associates

The 150-megawatt (MW) Kramer Junction plants shown here are part of a 354 MW series of SEGS (solar electric generating system) facilities, each using parabolic trough collectors to collect the sun's energy to generate steam to drive a conventional steam turbine. The plants have been operating in the California Mojave Desert for two decades.



Kramer Junction Company, NREL PIX 11070

Even if we consider only the high-value resources, nearly 7,000 gigawatts of solar generation capacity exist in the U.S. Southwest.

In June 2004, the Western Governors' Association (WGA) adopted a resolution to examine the feasibility of developing 30,000 megawatts (MW) of clean and diversified energy in the West by 2015. The Central Station Solar Task Force, one of the clean energy task forces commissioned as a result of this resolution, investigated the near-term potential of central station solar power to support the WGA goals. The task force found that, with federal and state policy support, 4 gigawatts (GW) of concentrating solar power (CSP) plants could easily be deployed in the southwestern United States by 2015.

CSP technologies include parabolic troughs, dish-Stirling engine systems, power towers, and concentrating photovoltaic systems (CPVs). CSP plants are utility-scale generators that produce electricity by using mirrors or lenses to efficiently concentrate the sun's energy to drive turbines, engines, or high-efficiency photovoltaic cells. CSP plants inherently generate maximum power on summer afternoons, near peak-demand periods. Trough and tower configurations include large power blocks for MW-scale output, whereas dish-Stirling and CPV systems are composed of a large number of smaller modular units.

Parabolic trough systems have been deployed in major commercial installations. Nine parabolic trough plants, with a combined capacity of 354 MW, have been operating in the California Mojave Desert for two decades. These plants were built as the result of attractive federal and state policies and incentives available for renewable energy projects at the time. More recently, renewable energy portfolio requirements have resulted in the construction of a 1-MW organic Rankine-cycle parabolic-trough plant in Arizona and the start of construction of a more conventional 64-MW steam-Rankine trough plant in Nevada. Construction of the 64-MW plant is scheduled for completion in early 2007.

Apart from the new construction described above, numerous projects are in various stages of development in the United States and worldwide. In the United States, California utilities are considering large deployments of CSP to satisfy the state's aggressive renewable portfolio standard (RPS). The RPS allows California utilities to rank bids for renewable generation using "least-cost, best-fit" criteria [1].

Generation from CSP technologies, especially those that can be augmented with thermal storage or hybridized with natural gas, is well matched with southwest load profiles, which tend to peak in the late afternoon and early evening. Because of this, California utilities appear eager to purchase large quantities of power from CSP technologies, if the price to the utilities is competitive with that offered by conventional gas turbine and combined cycle. For example, Phoenix-based Stirling Energy Systems signed power purchase agreements (PPAs) with Southern California Edison and San Diego Gas & Electric for two large CSP plant complexes in southern California. Whereas signed PPAs do not guarantee the plants will be built, they are an important and necessary first step, and indicate the industry's willingness to offer attractive prices for CSP-generated electricity.

Internationally, an attractive Spanish solar energy feed-in tariff has resulted in the announcement of proposed CSP installations composed of roughly 1,000 MW of new CSP capacity, primarily from parabolic trough systems using thermal storage. A utility in South Africa (ESKOM) is in the process of making a final decision on the deployment of a 100-MW power tower, and Israel is supporting the development of 500 MW of troughs. In addition, U.S. and German solar industries have developed a CSP Global Market Initiative (GMI), the goal of which is to deploy 5,000 MW of CSP power by 2010. The GMI was formally launched at the International Conference for Renewable Energies in Bonn, Germany, in 2004 and was supported by ministers from eight countries [2].

Resource Overview

CSP is unlike other solar technologies that are based on flat-surface collectors, such as rooftop solar-electric systems and solar water heaters. In contrast, CSP requires "direct-normal" solar radiation—the beam component of sunlight that emanates directly from the solar disk—and excludes diffuse, or "blue-sky," radiation.

Direct-normal solar radiation values can be derived from satellite data. Geostationary weather satellites, such as GOES, continuously monitor the Earth's cloud cover on a time and location basis. This information can be used to generate solar irradiance data that are time and site specific, leading to the generation of high-resolution maps of solar radiation [3]. Figure 1 describes the distribution of the direct-normal resource throughout the southwestern United States. The resource increases in intensity from the yellow areas through to the dark brown regions, but all are attractively high. States with suitably high solar radiation for CSP plants include Arizona, California, Colorado, Nevada, New Mexico, Texas, and Utah.

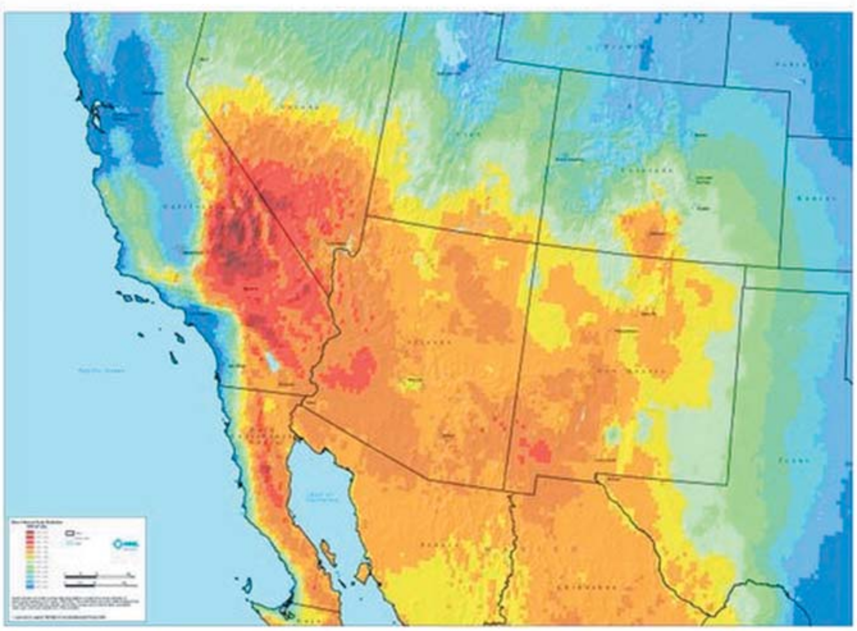


Figure 1. Direct-normal solar resource in the Southwest.

Not all the land area shown in Figure 1 is suitable for large-scale CSP plants, because such plants require relatively large tracks of nearly-level open land with economically attractive solar resources. To address this issue, Geographical Information System (GIS) data were applied on land type (e.g., urban, agriculture), ownership (e.g., private, state, federal), and topography.

The terrain available for CSP development was conservatively estimated with a progression of filters as follows:

- Lands with less than 6.75 kilowatt-hours per square meter per day (kWh/m^2/day) of average annual direct-normal resource were eliminated to identify only those areas with the highest economic potential.
- Lands with land types and ownership incompatible with commercial development were eliminated. These areas included national parks, national preserves, wilderness areas, wildlife refuges, water, and urban areas.
- Lands with slope greater than 1% and with contiguous areas smaller than 10 square kilometers (km^2) were eliminated to identify lands with the greatest potential for low-cost development.

Figure 2 shows the land area remaining when all of these filters are applied. Table 1 provides the land area and associated CSP generation capacity associated with the figure. This table shows that, even if we consider only the high-value resources, nearly 7,000 GW of solar generation capacity exist in the U.S. Southwest. According to the Energy Information Agency, in 2003, about 1,000 GW of generation capacity existed in the entire United States.

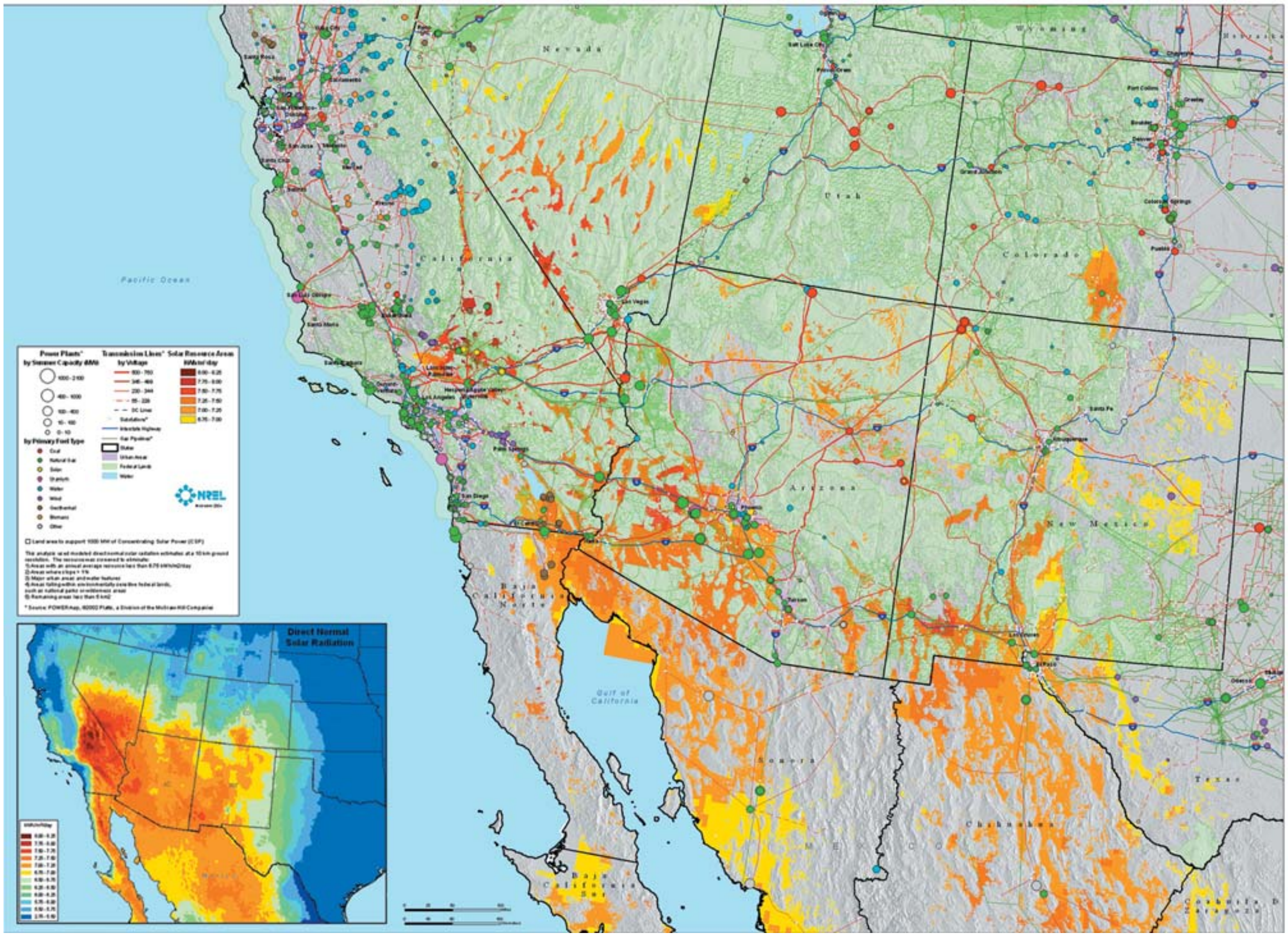


Figure 2. Direct-normal solar radiation, filtered by resource, land use, and topography.

Table 1.
Results of satellite/GIS analysis showing area of land and associated generation capacity for seven states in the Southwest.

State	Available Area (mi^2)	Capacity (MW)*
Arizona	19,300	2,467,700
California	6,900	877,200
Colorado	2,100	271,900
Nevada	5,600	715,400
New Mexico	15,200	1,940,000
Texas	1,200	148,700
Utah	3,600	456,100
Total	**53,900**	**6,877,000**

* CSP power plants require about 5 acres of land area per megawatt of installed capacity. Solar generation can be estimated by assuming an average annual solar capacity factor of 25% to 50%, depending on the degree of thermal storage used for a plant.

Supply and CO_2 Reduction Curves

Capacity supply curves were developed for central station CSP plants based on guidance provided by the WGA in support of its initiative to examine the feasibility of bringing online 30,000 MW of clean and diversified energy by 2015. Supply curves provide a means for describing the relative cost of generation for a particular technology (renewable or conventional) and the generating capacity coincident with the cost. For renewable technologies, costs are driven primarily by two factors—resource availability and proximity to available transmission.

The supply curves described by Figure 3 below are based on the current "busbar" cost (technology costs exclusive of transmission) of a 100-MW parabolic trough plant with 6 hours of thermal storage. For a single-axis tracking parabolic trough plant, the busbar costs vary as a function of solar resource and latitude. For this analysis, the land area available for development was based on the same filters used to generate the resource map provided in Figure 2. Generation costs are presented in nominal dollars, per guidance provided by the quantitative working group of the WGA's Clean and Diversified Energy Committee (CDEAC).

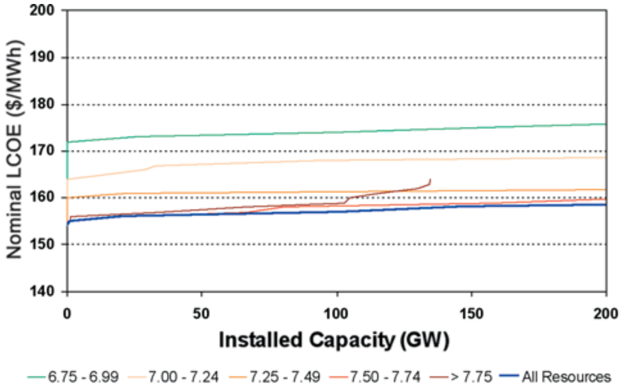


Figure 3. Supply curves describe the potential capacity and current busbar costs in terms of nominal levelized cost of energy (LCOE).

Figure 4 shows an extension of this analysis based on the assumption of 20% transmission-capacity availability to the nearest load center(s). Where the solar resource is located adjacent to a load center, 20% of city demand is assumed to be available to off-take the solar generation without the need for new transmission. The analysis assumes that when the 20% capacity is allocated, new transmission must be built to carry additional supply to the nearest load center. New transmission cost is assumed to be $1,000 per MW per mile.

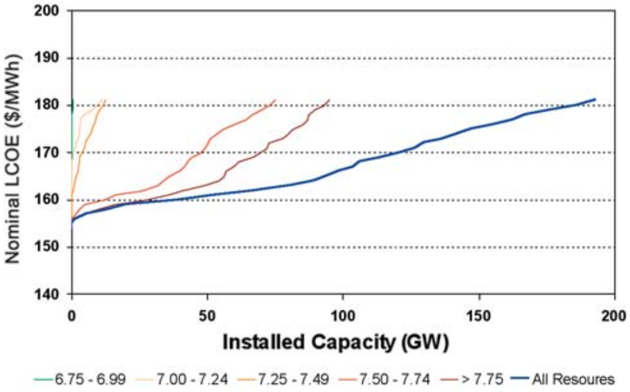
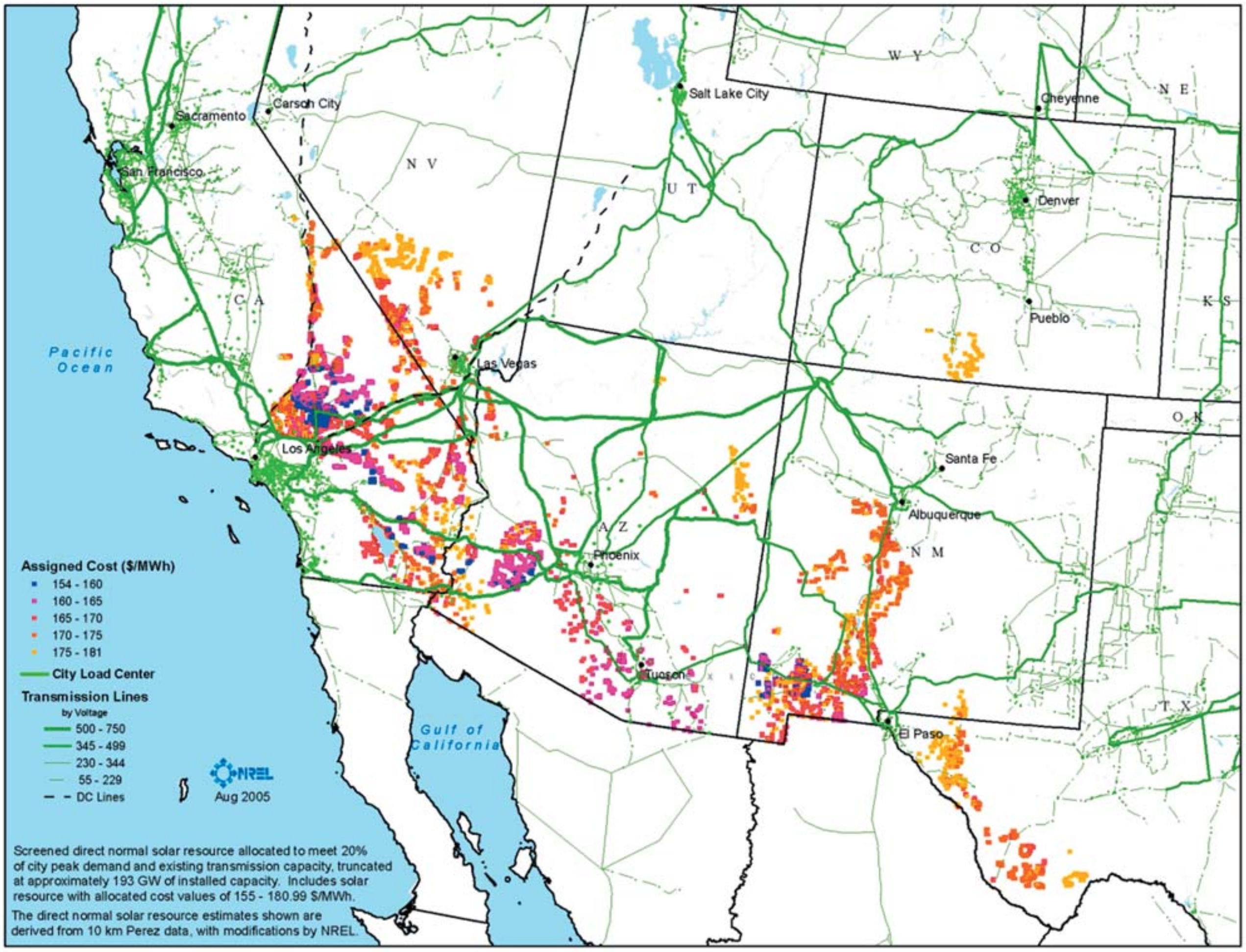


Figure 4. CSP supply curve based on 20% availability of city peak demand and 20% availability of transmission capacity.

Figure 5 shows the location of up to 200 GW of potential CSP plants coincident with the data shown in Figure 4. As previously described, optimal sites are located in areas of high solar resource near available transmission or where new transmission can be built at minimal cost to the project.



Screened direct normal solar resource allocated to meet 20% of city peak demand and existing transmission capacity, truncated at approximately 193 GW of installed capacity. Includes solar resource with allocated cost values of 155 - 180.99 $/MWh.

The direct normal solar resource estimates shown are derived from 10 km Perez data, with modifications by NREL.

Figure 5. Optimal locations for CSP plants based on supply curve analysis.

Because supply curves are essentially a snapshot in time, they do not account for cost reductions due to levels of deployment commensurate with the capacity depicted on the curves. Similarly, they do not show cost reductions associated with research and development (R&D) efforts planned within the United States and abroad. An analysis developed for the U.S. Department of Energy's (DOE's) Solar Energy Technologies Program (SETP) multiyear program plan [4] describes cost reductions for parabolic trough systems based on a combination of continued R&D, plant scale-up, and deployment. For this analysis, deployment levels were conservatively estimated at 4 GW by 2015, based on consensus within the WGA working group. Results of this analysis are given in Figure 6.

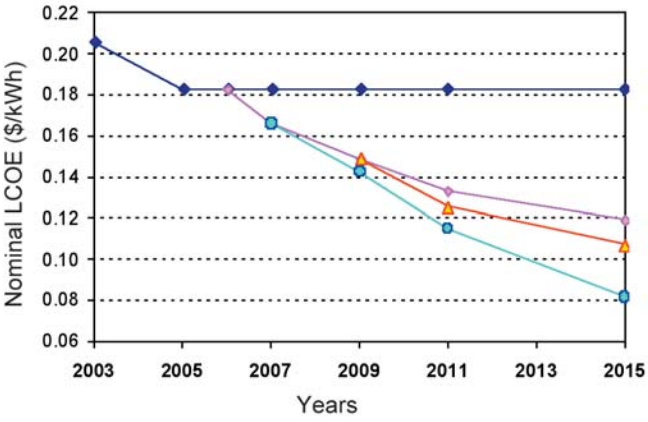


Figure 6. Projected cost reductions for parabolic trough systems out to 2015.

Assumptions behind these cost reductions are described fully in the SETP multiyear plan.

While the WGA was interested in projections of clean energy penetration out to 2015, additional analysis has been undertaken to assess the longer-term impact of policies recommended by the WGA Solar Task Force [5]. The primary policy of interest is the recommended extension of the current 30% federal investment tax credit (ITC) to 2017.

Figure 7. CSP capacity deployment by region in 2030 based on output from Concentrating Solar Deployment System Model (CSDS).

Using the Concentrating Solar Deployment System Model (CSDS), developed recently by the National Renewable Energy Laboratory (NREL), preliminary results indicate that up to 30 GW of parabolic trough systems with thermal storage could be deployed in the Southwest by 2030 under an extension of the 30% ITC [6]. Under a more aggressive scenario assuming the introduction of a $35/ton of CO_2 carbon tax, the results indicate penetration levels approaching 80 GW by 2030. CSDS is a multi-regional, multi-time-period model of capacity expansion in the electric sector of the United States and is currently being used to investigate policy issues related to the penetration of CSP energy technologies into the electric sector. The model competes parabolic troughs with thermal storage (based on fixed capital and variable operating costs over 16 annual time slices) against fossil fuel, nuclear, and wind generation technologies. Costs for nonrenewable generation are based on the EIA's Annual Energy Outlook 2005. Figure 7 identifies the regions where this new capacity will be developed.

Using parabolic-trough cost projections for 2015 based on the SETP multi-year plan analysis and cost projections for 2030 based on output from CSDS, additional busbar supply curves were developed. These curves are shown in Figure 8.

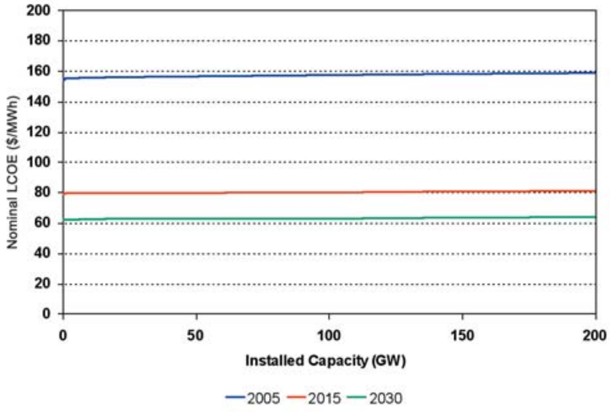


Figure 8. Busbar supply curves (all solar resources > 6.75 kWh/m^2/day) based on current costs and cost projections for 2015 and 2030.

The relative flatness of the supply curves shown in Figure 8, as well as those shown in Figures 3 and 4 (note change in scale of y-axis), is a direct result of the GIS-based resource and land-screening process, which demonstrated the large amount of land available in high-resource areas. Extension of this analysis to include the identical transmission constraints used to develop Figure 4 results in the supply curves shown in Figure 9. It should be noted that the supply curves in the figure are based on the current transmission grid. However, they provide a qualitative assessment of the cost of energy from future CSP plants, because the curves include the cost of constructing new transmission to areas where lines do not currently exist.

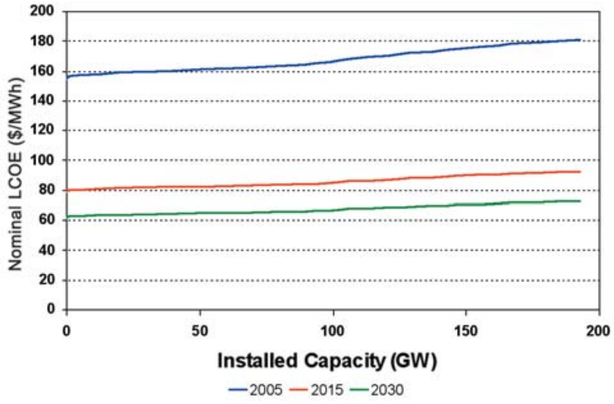


Figure 9. Transmission constrained supply curves (all solar resources > 6.75 kWh/m^2/day) based on current costs and cost projections for 2015 and 2030.

Future carbon displacements based on the penetration and costs described by the supply curves in Figure 9 were estimated using a conversion factor of 210 metric tons of carbon (tC) per gigawatt-hour (GWh) of displaced generation. Prior to using this conversion factor, the capacity described by the supply curves was converted to electric generation based on capacity factors commensurate with the solar resource available. Table 2 describes the capacity factors for a parabolic trough plant with 6 hours of thermal storage as a function of resource class.

Table 2.
Capacity factors for a trough plant with thermal storage as a function of solar resource level.

Resource	Capacity Factor
7.75 - 8.06 kW/m^2/day	0.457
7.50 - 7.74 kW/m^2/day	0.442
7.25 - 7.49 kW/m^2/day	0.427
7.00 - 7.24 kW/m^2/day	0.413
6.75 - 6.99 kW/m^2/day	0.409

Using these factors and a refinement of solar resource within the supply curve (examples of this refinement are shown in Figures 3 and 4), a series of carbon reduction curves was developed. These curves are shown in Figure 10.

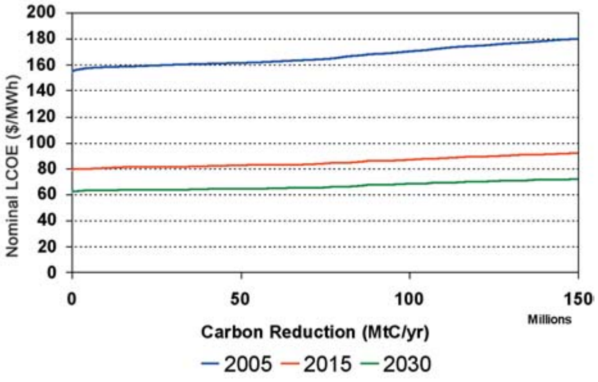


Figure 10. Million metric tons of carbon (MtC) avoided based on current and projected transmission constrained supply curves.

The curves demonstrate that significant carbon reductions are possible at low cost, if cost targets for CSP systems are achieved.

Conclusions

The solar resource in the Southwest is very large. GIS screening analysis shows that there is ample highly suitable land to support large-scale CSP deployment. Capacity supply curves based on the screening analysis demonstrate that suitable lands are located close to existing transmission, minimizing costs required to access high-value solar resources.

Analysis done for the WGA's Clean and Diversified Energy Solar Task Force indicates that as much as 4 GW of new CSP capacity could be installed in the Southwest by 2015, if policies recommended by the task force are accepted. Preliminary results using the NREL-developed CSDS indicate that up to 30 GW of CSP capacity could be achieved by 2030, if the current federal solar ITC is extended beyond its current 2-year period. 80 GW of CSP capacity is possible under a more aggressive policy scenario that includes a carbon tax of \$35/ton CO_2.

With an extension of the current ITC, we estimate carbon displacements approaching 25 MtC per year. Carbon displacements approaching 65 MtC per year are possible under the more aggressive policy scenario.

Acknowledgements

The authors would like to acknowledge the NREL resource assessment and GIS teams for their extensive analysis in support of this work and Nate Blair at NREL for his effort in developing the Concentrating Solar Deployment Systems Model.

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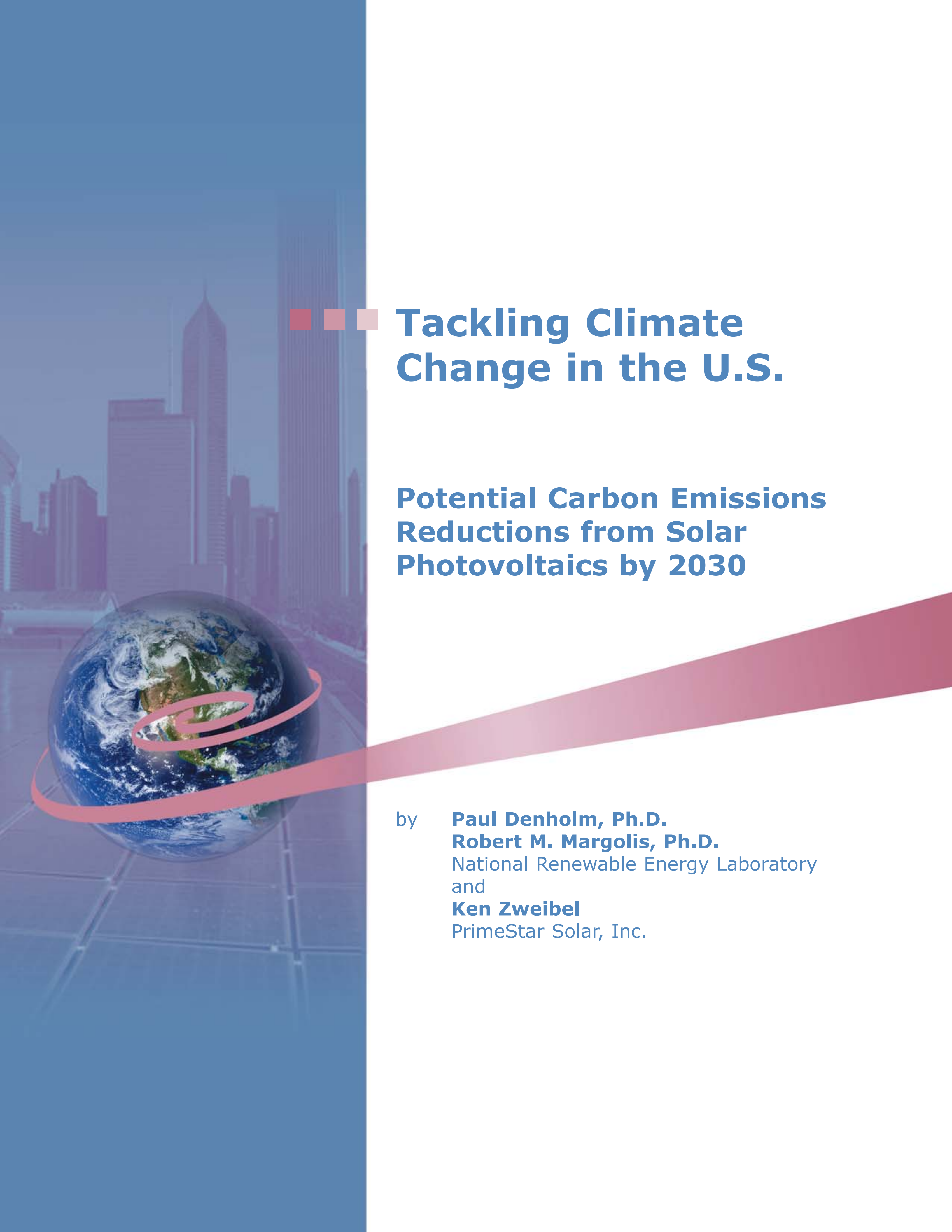

Tackling Climate Change in the U.S.

Potential Carbon Emissions Reductions from Solar Photovoltaics by 2030

by **Paul Denholm, Ph.D.**
Robert M. Margolis, Ph.D.
National Renewable Energy Laboratory
and
Ken Zweibel
PrimeStar Solar, Inc.


Spire Solar Chicago, NREL PIX 13789

This 130-kilowatt photovoltaic (PV) system on the Art Institute of Chicago generates electricity without producing greenhouse gases.

The basic resource potential for solar PV in the United States is virtually unlimited compared to any foreseeable demand for energy.

Solar photovoltaics (PV) convert light into electricity using semiconductor materials. PV is typically deployed as an array of individual modules on rooftops, building facades, or in large-scale ground-based arrays. PV systems produce direct current (DC), which must be converted to alternating current (AC) via an inverter if the output from the system is to be used in the grid.

Annual production of PV modules in 2005 was about 150 megawatts (MW) in the U.S. and about 1.7 gigawatts (GW) worldwide [1]. The PV industry has grown at a rate greater than 40% per year from 2000 through 2005. Much of this growth is the result of national and local programs targeted toward growing the PV industry and improving PV's competitiveness in the marketplace.

In 2006, the U.S. Department of Energy (DOE) proposed the Solar America Initiative, with the goal of deploying 5 to 10 GW of PV by 2015. This program focuses on bringing down the cost of PV technology, which would enable even greater deployment of distributed PV generation. The 5 to 10 GW goal represents only a tiny fraction of solar PV's potential.

A major goal of the U.S. Department of Energy's (DOE) Solar Energy Technologies Program is to increase solar PV efficiency and decrease costs [2]. The first solar cells, built in the 1950s, had efficiencies of less than 4%. The efficiency of PV cells has increased substantially over time, with current efficiencies for commercial crystalline silicon cells equal to about 15% to 20%. The average efficiency range of PV modules (made up of strings of cells) is lower—10% to 15% for commercial crystalline silicon (c-Si) modules and 5% to 10% for commercially available thin-film PV modules.

The total costs of PV systems are currently in the \$6 to \$9 per peak watt (W_p) range. Component costs include the PV modules at about \$3 to \$4/W_p (DC), with another \$3 to \$5/watt for the inverter, installation, and balance of system. Historical data on modules have been tracked closely over the past couple of decades. Thus, Figure 1 provides the historical price and cost targets for PV modules.

If the PV industry can achieve cost reductions in line with industry and DOE targets over the next decade, then PV could become widely cost-competitive in the United States, particularly in places with high electricity prices and good solar resources such as California [3]. Initiatives such as the California Solar Initiative and the recently proposed federal Solar America Initiative are intended to create new markets for PV while fundamentally improving the technology and lowering costs. Beyond the installed cost of PV, the cost competitiveness of solar-generated electricity is location-specific, depending on both the local cost of electricity and the quality of the solar resource.

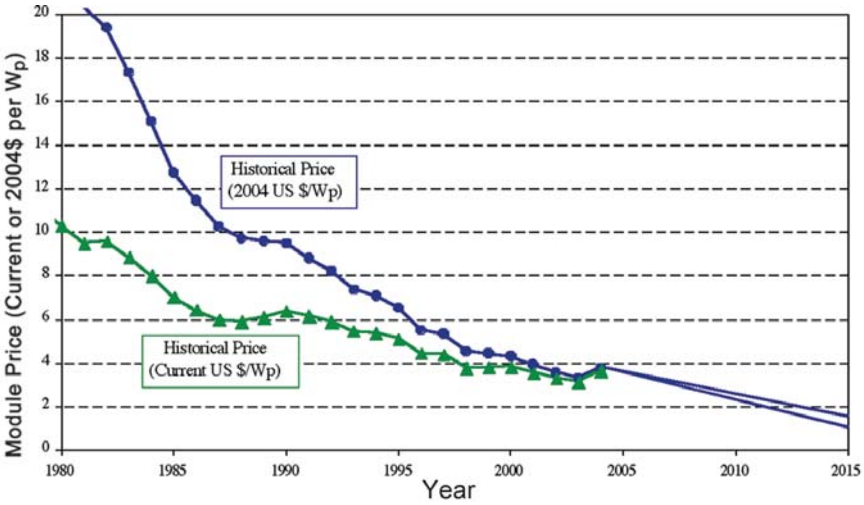

Figure 1. Historical PV module price and current price targets.

Resource Overview

While there is usable solar resource in all of the United States, there is significant variation in the quality of this resource. The quality of solar resource can be measured by the total insolation, or amount of solar energy striking a flat surface over time. A common measure of insolation is average energy per unit area per day or kilowatt-hour per square meter per day (kWh/m^2/day). Note that the energy value is the solar energy incident on a PV panel surface—not the electrical output of a PV array. The measured insolation value depends on the orientation of the collector. A panel may be laid flat (horizontal) to minimize installation costs on a rooftop, or may be tilted at a south-facing angle to increase the amount of radiation captured. The range of average insolation in the United States on a flat, horizontal surface is roughly 3.0 to 5.8 kWh/m^2/day, with the best resources in the desert Southwest, and the worst resources in the Pacific Northwest [4]. When tilted south to capture a larger amount of solar energy, this insolation value increases about 10% to 15%. In addition, solar PV may be deployed in tracking arrays that follow the sun to provide a maximum annual output. The range of insolation for tracking arrays in the United States is about 4.4 to 9.4 kWh/m^2/day. The total incident solar energy on the land area of the continental U.S. is about 5 x 10^{13} kWh/day. For comparison, the average daily electricity consumption in the United States in 2004 was about 1 x 10^{10} kWh [5].

Figure 2 provides an overview of the variation of solar resource in the United States. This particular map measures insolation on a flat surface facing south at latitude tilt.

To translate insolation values to usable electricity values, the PV conversion efficiency must be applied. As mentioned previously, typical efficiency of commercial PV modules is around 5% to 15%, depending on type. Losses in the inverter, wiring, and other balance-of-system components reduce output by another 10% to 20%. As a result, the overall AC rating of a PV system is typically around 80% of its DC rating. In this work, we refer to a PV system in terms of its peak AC output. Based on a round-number 10% system efficiency assumption, the daily U.S. solar PV resource base is reduced to about 5 x 10^{12} kWh/day.

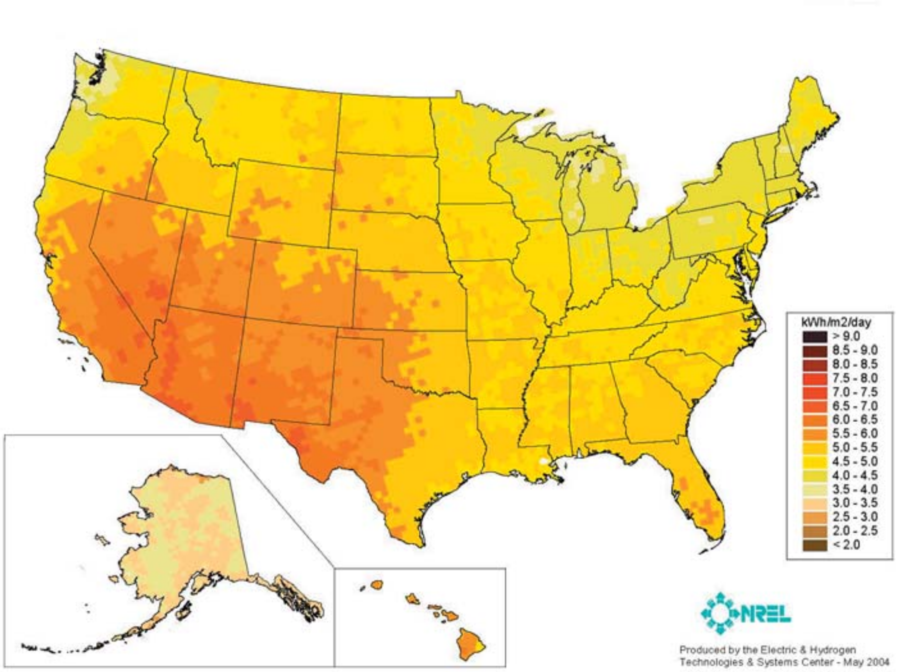

Figure 2. Solar PV resource map for the United States using flat, south-facing surfaces at tilt equal to latitude.

Given the vast resource base, any supply curve for PV is necessarily limited in scope. Beyond variation in geographical resource, there are a number of factors that affect the potential availability and price of PV-generated electricity, including rooftop availability and land use constraints (see **Rooftop and Land Availability,** below), intermittency, transmission constraints, and material availability. We discuss each of these factors, and then provide a sample PV supply curve noting the caveats and assumptions used in our analysis.

Intermittency

The intermittency of the solar resource limits its ultimate contribution to the grid if storage is not widely deployed. Without storage, PV cannot meet demand during evenings and on overcast days. Even without storage, however, PV can make a significant contribution, particularly because PV output is generally correlated with demand on hot, sunny afternoons. PV output generally peaks in the summer when demand is greatest in most of the U.S.

Rooftop and Land Availability

PV can be deployed on rooftops or in ground-based distributed and utility-scale applications. Rooftop deployment has the advantage of incurring zero land use costs, although opportunity costs are not necessarily zero when competing with other solar technologies (water heating, daylighting) or other uses such as green roofs. A significant advantage of rooftop deployment is the minimal transmission and distribution (T&D) requirements (and losses), because most of the energy is used at the point of generation.

The rooftop area, and therefore potential space for PV in the United States, is very large. Two previous estimates of the total available roof space for PV in the United States are 6 and 10 billion square meters, even after eliminating 35% to 80% of the total roof space due to shading and inappropriate orientation [6,7]. The lower value also does not include certain industrial and agricultural buildings. While fairly rough estimates, these values provide some idea of the potential resource base. Assuming a typical PV system performance of 100 watts per square meter (W/m^2) (equivalent to an average insolation of 1000 W/m^2 and a 10% AC system efficiency), this rooftop area represents a potential installed capacity of 600 to 1000 GW. At an average capacity factor of 17%, this installed capacity could provide 900-1500 terawatt-hours (TWh) annually. This represents about 25% to 40% of the total U.S. electricity consumption in 2004.

If building area grows at the same rate as electricity consumption, this PV potential (in terms of fractional energy supply) will remain constant. However, because the efficiency of PV modules is expected to substantially increase over time, the PV potential on rooftops could also increase. In addition, this rooftop potential does not consider parking structures or awnings or south-facing building facades.

Beyond rooftops, there are, of course, many opportunities for PV on low (or zero) opportunity cost land such as airports (which have the added advantage of being secure environments), and farmland set-asides. Land-based solar PV may be deployed in “tracking” arrays, which could increase the annual output by 25% or more, and decrease the amount of land required.

This preliminary assessment indicates that non-zero-cost land set aside specifically for solar PV generation will not need to occur until this technology provides a very large fraction (perhaps more than 25%) of the nation’s electricity.

As the penetration of PV into the marketplace increases, dealing with the intermittent nature of the technology will require deploying enabling technologies (such as storage) or a significant fraction of PV output may be unusable [8]. The cost impacts of high penetration renewable systems are still largely unknown, with limited work available on utility-scale PV impacts. If storage is available at a reasonable cost, PV generation itself could potentially provide the majority of a system's electricity. Finding alternative uses for excess mid-day PV generation, such as in plug-in hybrid electric vehicles, could also increase penetration of PV. Here, we artificially restrict our analysis to a non-storage case and assume that PV can provide up to 10% of a system's energy without a significant cost penalty.

Transmission

We expect that at our assumed level of penetration (up to 10% on an energy basis), PV generation and use will be geographically coincident and will require no additional transmission. However, additional transmission availability could lower the cost of PV-generated electricity by allowing high-quality, lower cost solar PV resources to be used in locations with relatively poor solar resource. Transmission would also potentially reduce the intermittency impacts by increasing spatial diversity.

For simplicity, we restricted this analysis to exclude these potential benefits of transmission and require all electricity generated from PV to be used locally.

Material Availability

Certain advanced PV technologies, particularly thin-film PV, use a variety of rare materials. These materials include indium, selenium, tellurium, and others. Resource constraints on these types of materials could restrict the ultimate deployment of some PV technologies. However, without considering new reserves, the known conventional reserves of these materials are sufficient to supply at least several tens of peak terawatts (TW_p) of thin-film PV [9]. For many other PV types, such as c-Si, materials supplies are virtually unlimited compared to any foreseeable demand.

PV Cost

DOE's Solar America Initiative has aggressive goals for reducing the cost of PV systems. Figure 3 provides a plot of PV cost reduction targets for residential (2-4 kilowatt [kW]) systems in 2015 and 2030. These are not predictions but goals based on an adequate and sustained research and development (R&D) effort. Achieving these goals would bring the cost of residential electricity from solar PV to around 10 to 12 cents/kWh by 2015 and 6 to 8 cents/kWh by 2030. Costs for commercial scale (10 to 100 kW) and utility scale (1 MW or greater) are expected to be lower. The expected price reduction should come from module cost reductions, module efficiency improvements, economies-of-scale for aggregated and larger PV markets, and improved system designs.

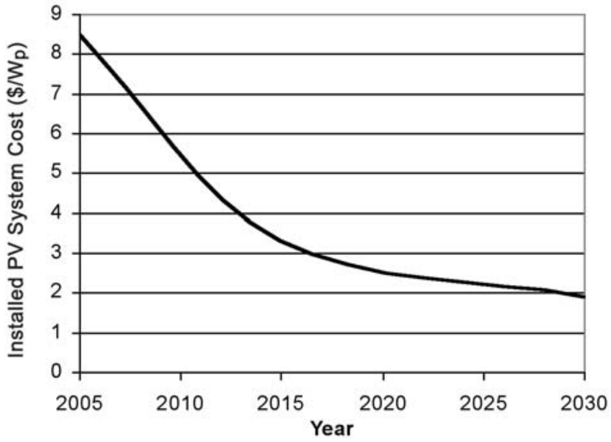

Figure 3. Technology cost reduction goals for residential PV systems.

PV Supply Curve Based on Geographic Variability

Using the assumptions described above, we generated a supply curve for solar PV energy in the United States. This supply curve is based on the constraint that PV may provide up to 10% of the electricity in a region, limited by intermittency and transmission. Because our assumptions require PV energy to be generated and used locally, the cost is driven exclusively by geographic variability of resource. To generate a supply curve, we divided the country into 216 supply regions (based on locations of recorded solar data) [10], and calculated the cost of PV-generated electricity in each region, based on simulated PV system performance. We calculated the price in each region using PV system cost targets for 2005, 2015, and 2030.

The amount of PV in each cost "step" is based on the capacity required to meet 10% of the region's total electricity demand. We estimated each region's total electricity demand from population and state level per-capita electricity consumption data. Electricity consumption for 2015 and 2030 was based on projected national demand growth, minus the energy efficiency potential under an aggressive carbon reduction policy [11,12]. Figure 4 provides the resulting PV energy supply curve. We cut off the 2005 curve due to the very high price of PV electricity (>25 cents/kWh) even in relatively high-quality resource areas (this analysis does not include any existing subsidies).

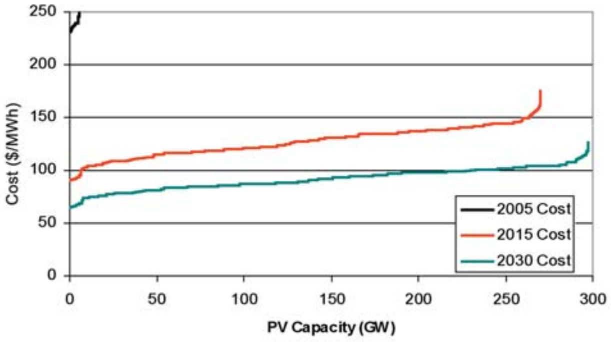

Figure 4. PV capacity supply curves.

The limits to our assumptions (particularly limiting PV's contribution on a fractional basis) can be observed in Figure 4. Because we only allow PV to provide 10% of a region's energy, the absolute amount of energy is restricted in the 2015 curve. In reality, it should be possible to extend the supply curve to the right by considering scenarios involving transmission or considering possible cost impacts of intermittency. Including transmission could also potentially "flatten" the supply-cost curve, given the possibility of increased use of high-quality resources.

Figure 5 translates the PV capacity values into potential carbon reduction. At each site, annual energy production was estimated and assumed to displace carbon emissions at a rate of 210 metric tons of carbon per gigawatt-hour (GWh).

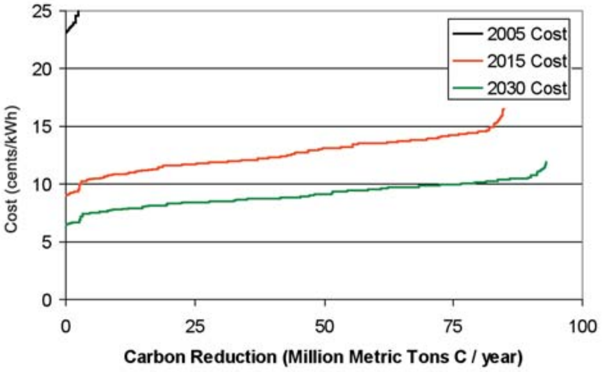

Figure 5. Carbon reduction curves for solar PV.

Possible Deployment Versus Time

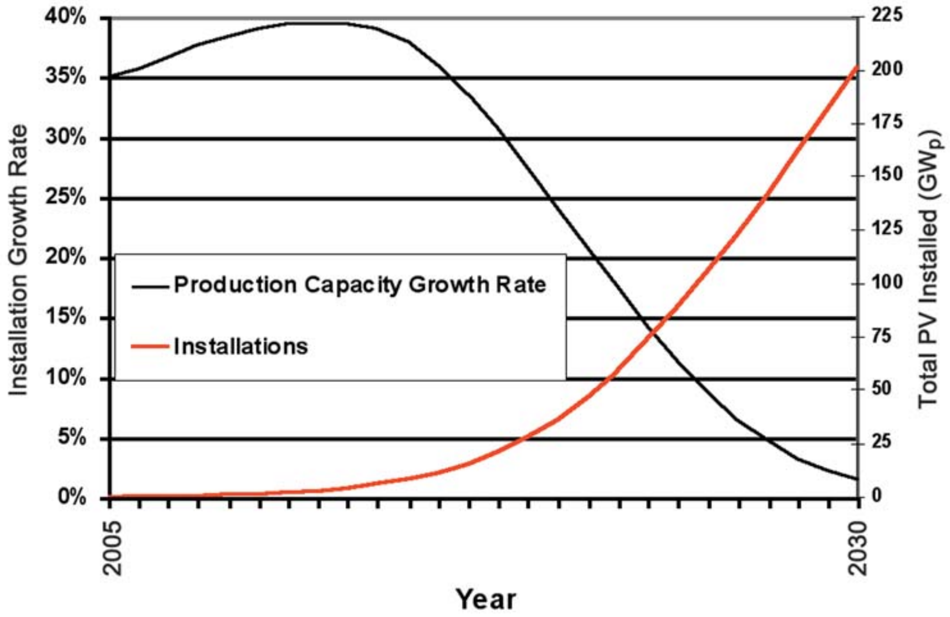

Figure 6: Growth scenario allowing PV to reach 200 GW of capacity and 7% of total U.S. electricity by 2030.

The supply curves previously provided do not consider the actual market adoption of PV under a carbon constraint scenario or the required growth rate in production and installation capacity. To illustrate one possible scenario for PV growth, we considered the U.S. Photovoltaics Industry Roadmap goal of deploying 200 GW of PV by 2030. Figure 6 illustrates a possible scenario for PV growth that results in PV reaching this goal. This figure is not intended to be a prediction or even a "likely" scenario—we used it only to illustrate one of many possible scenarios of PV industry growth. In this scenario, total U.S. PV installations in 2030 would reach 200 GW and provide about 7% of total U.S. electricity.

Because PV has a relatively low capacity factor (typically 20% or less) compared to other generators, a relatively large capacity is required to meet significant energy demand.

If we assume that the 200 GW of PV is uniformly distributed (based on population) across the United States, then this level of PV deployment would produce about 298 TWh annually. Assuming a marginal grid emissions range of 160 to 260 Mt of carbon/GWh, this level of PV penetration would reduce U.S. carbon emissions by 48-78 million metric tons of carbon per year (MtC/yr).

In this scenario, total U.S. PV installations in 2030 would reach 200 GW.

Conclusions

The basic resource potential for solar PV in the United States is virtually unlimited compared to any foreseeable demand for energy. Practically, deployment of solar PV on the scale necessary to have a significant impact on carbon emissions is contingent on a number of factors. PV is currently among the more costly renewable technologies, but has significant potential for reduced costs and deployment on a wide scale. Sustained cost reductions will require continued R&D efforts in both the private and public sectors. Significant growth will be needed in the scale of PV manufacturing both at the aggregate and individual plant levels. For example, production economies of scale will likely require the annual output of individual PV plants to increase from a current level of tens or at most a few hundreds of MW per year to GW per year. Finally, institutional barriers, including the lack of national interconnection standards for distributed energy and net-metering provisions, will need to be addressed.

In the scenario we evaluated here, in which 200 GW of solar PV provides about 7% of the nation's electricity, PV is unlikely to be burdened by constraints of intermittency, transmission requirements, land use, or materials supplies. Available roof space (and zero- to low-cost land) and known materials can provide resources far beyond this level of PV use. In the long term, at some point beyond this level of penetration, intermittency poses a more significant challenge, likely requiring large-scale deployment of a viable storage technology. However, as part of a diverse mix of renewable energy technologies, solar PV by itself can play a valuable role in reducing carbon emissions from the electric power sector.

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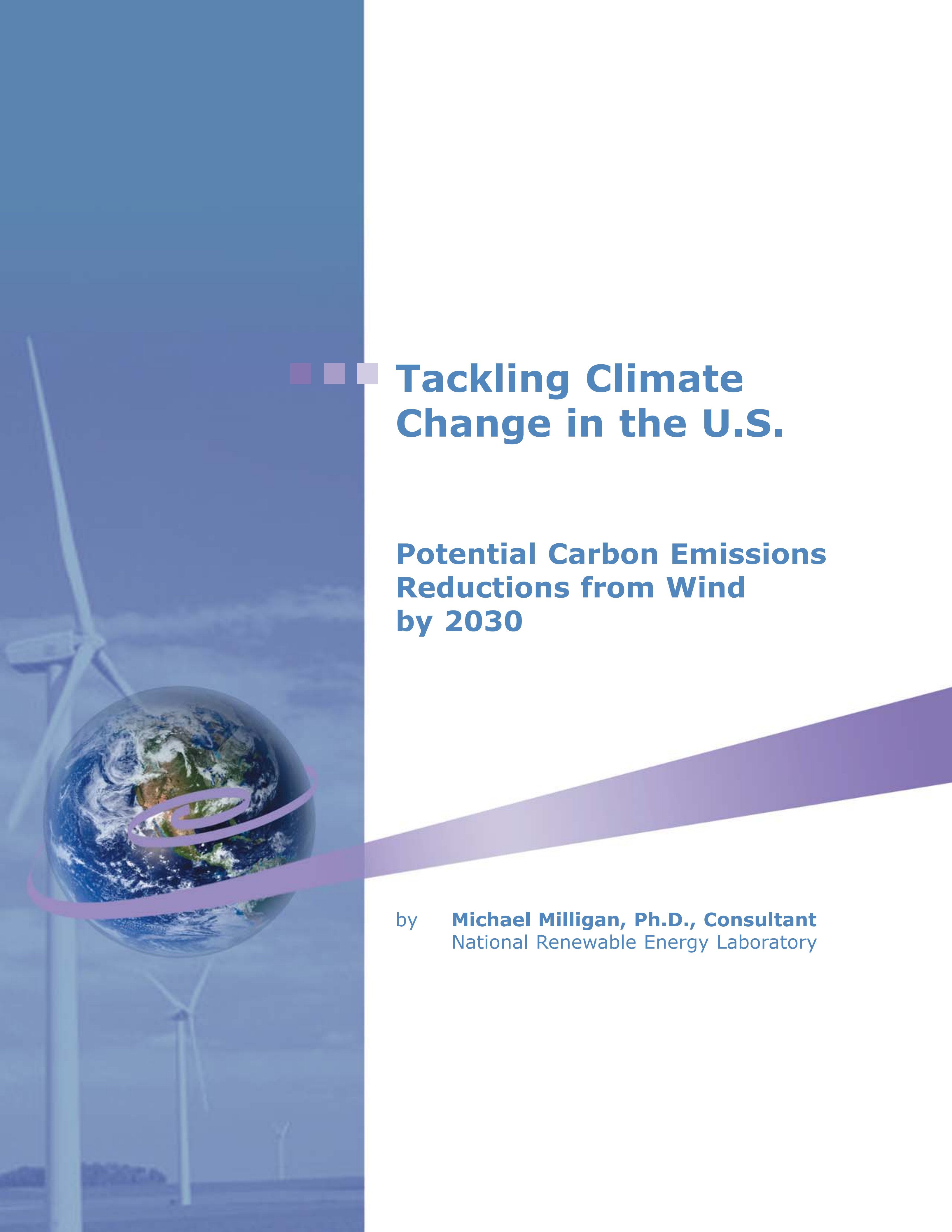


Tackling Climate Change in the U.S.

Potential Carbon Emissions Reductions from Wind by 2030

by **Michael Milligan, Ph.D., Consultant**
National Renewable Energy Laboratory

This 135-turbine wind project located north of Blairsburg, Iowa, consists of 100 GE 1.5SE 1.5 megawatt (MW) turbines (pictured here) and 35 Mitsubishi MWT-1000 1.0 MW turbines.

Todd Spink, NREL PIX 14820

We estimate that the widespread use of wind power will result in the cumulative avoidance of 1,100 to 1,780 million metric tons of carbon by 2030.

Modern wind turbines have evolved significantly in the past few years. In the United States, the typical modern turbine has a generating capacity exceeding 1 megawatt (MW) and a hub height of 80 meters from the ground. Recent wind power plants may consist of projects owned by several entities and have aggregate capacity in the hundreds of megawatts.

Energy produced by a wind turbine depends on the wind, which is a variable resource over several time scales. This variability is cause for concern among power system operators, who are responsible for maintaining system balance. During the past few years, several comprehensive wind integration studies have analyzed the power system's ability to incorporate wind. The U.S. studies show a modest cost ranging up to about $5 per megawatt-hour (MWh) for the ancillary service impact of wind. This is the additional cost that wind imposes in the process of maintaining electrical system balance. Most integration studies involve detailed chronological power system simulations that mimic the overall power system operation with wind. To date, the variability of wind does not appear to be a significant hindrance to its use as an energy resource, although the specific impacts and costs would vary from system to system and would depend on the size of the wind plant relative to the balancing authority.

The pattern of wind generation may not match loads on a seasonal or diurnal basis. Wind is primarily an energy resource, but it can displace other capacity at a relatively small fraction of its rated capacity.

Our task here is to examine the potential for wind power to displace carbon as part of a broader scenario that addresses the contribution that renewable energy can make to mitigate climate change. To provide plausible estimates of this carbon reduction, we must first develop reasonable scenarios that illustrate the role that wind power can play in the overall portfolio of electrical generation facilities.

One source we used to accomplish this is the report of the Wind Task Force (WTF). The Western Governors' Association's (WGA's) Clean and Diversified Energy Advisory Committee (CDEAC) convened the WTF to assess the feasibility of achieving 30,000 MW of clean and diversified energy in the West by 2015. The WTF examined the near-term potential of wind energy in the West, using a combination of technical supply curves based on geographical information system (GIS) data and information from recent utility and transmission studies. The study results indicate a very large potential for wind generation in the West. Supplementing the GIS analysis is information extracted from utility integrated resource plans (IRPs) that include wind additions in the near term, along with estimates of wind development that will be

> *To date, the variability of wind does not appear to be a significant hindrance to its use as an energy resource.*

induced by state renewable portfolio standards (RPSs). However, these results depend on federal and state policy support and transmission access.

During 2005, approximately 2,500 MW of wind generating capacity was installed in the United States. According to the American Wind Energy Association [1], current U.S. wind capacity stands at 9,149 MW. The WTF used a recent analysis [2] to estimate potential wind that would come online by 2015 in response to state RPSs in the West. According to the WTF, new wind capacity induced by these RPSs could range from about 5,600 MW to about 10,200 MW by 2015. Utility IRPs in the West may also result in about 3,600 MW of new wind capacity by 2015. And recent volatility in natural gas prices has had a significant impact on utilities that burn gas to produce power. In some cases, wind energy is the cost-effective choice, further stimulating wind development.

In the United States, a production tax credit (PTC) that reduces the effective cost of wind generation has been in place over the past few years. Unfortunately, the PTC expired in 2004, causing wind development in the United States to nearly cease. When the PTC was renewed, wind development that had been on hold quickly materialized, causing an enormous increase in the demand for turbines. Because of this large swing in turbine demand, manufacturers have had difficulty providing sufficient turbines to the market, and prices have increased. Combined with higher steel prices and unfavorable currency exchange rates, 2005 and 2006 experienced a significant increase in turbine costs. Because of the complex interaction of all the contributing factors to this cost increase, it is not clear whether the current prices represent a temporary condition or whether turbine costs are on an upward trend. The WTF report discusses this issue in more detail.

With this overview as a backdrop, we developed estimates of wind's contribution to carbon reduction. It is important to note that the estimates contained here are not forecasts. Rather, they are estimates based on the potential of wind development that may or may not be achieved. The extensive GIS database that describes the wind potential in the United States has limitations and may underestimate wind potential.

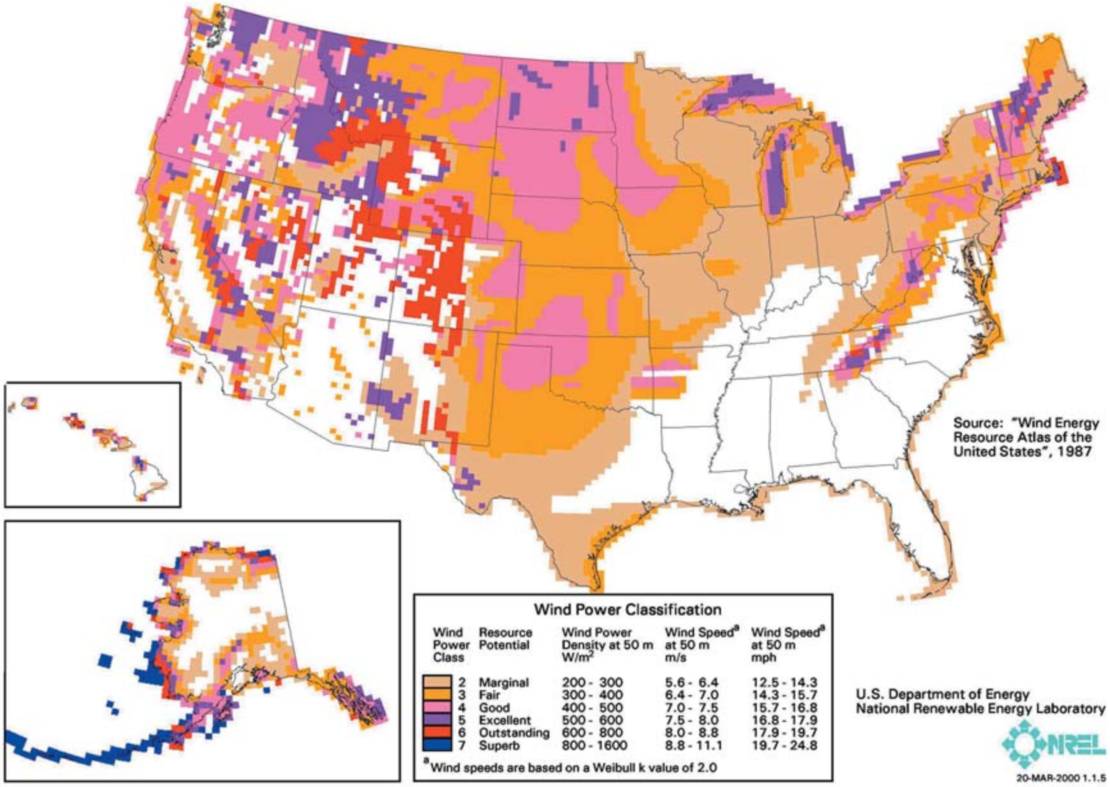
On the other hand, there are uncertainties involving the application of this data to modern and evolving wind turbine technology that may work in the opposite direction. The high wind generation scenario in this paper assumes continued policy support such as the current Federal Production Tax Credit, innovative business arrangements such as flexible-firm transmission tariffs (in the West), and quite possibly control area cooperation in some regions to better handle the variable nature of the wind resource. In some cases there may be a need for technology that does not currently exist, or is costly in today's terms, that would help manage wind's variability. The scenario is aggressive and possible, but may not unfold without clear national direction and focus on mitigating climate change.

In some cases, wind energy is the cost-effective choice, further stimulating wind development.

The National Renewable Energy Laboratory (NREL) has assembled a comprehensive GIS system for renewable generation. The GIS dataset for wind is based on a large-scale meteorological simulation that "re-creates" the weather, extracting wind speed information from grid points that cover the area of interest. Mapping processes are not always directly comparable among the states, but NREL has validated maps from approximately 30 states.

The wind can exhibit many different patterns that vary over time and space. During the fall and spring seasons, it is common to observe more wind than during other months. Wind patterns also may not match load patterns, limiting wind's capacity contribution to the grid. Wind shear, the difference in wind velocity at different elevations from the ground, is pronounced in many parts of the United States. Because the GIS database contains wind speed at 50 meters (m) from the ground, this creates a mismatch with currently available wind turbines with a hub height of 80 m. In the next few years it is likely that hub heights will increase further, to 100 m (as is becoming common in Europe) or even higher. This implies that the estimates of the wind resource shown by the map likely understate the wind resource, perhaps significantly, resulting in supply curves that also understate the quantity of wind at various prices.

Figure 1 shows the U.S. wind resource map [3]. Many states have higher-quality maps that we used for this analysis. As the U.S. map shows, the upper Great Plains states and the West generally have a significant wind resource, and there are other areas of the country that also have good wind. Although the map shows offshore resources, we only considered onshore in the supply curve analysis because the offshore technology and costs have not matured sufficiently. We did not include Alaska and Hawaii in the analysis.



Wind Power Classification

	Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m^2	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
🟧	2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
🟧	3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
🟪	4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
🟪	5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
🟥	6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7
🟦	7	Superb	800 - 1600	8.8 - 11.1	19.7 - 24.8

[a] Wind speeds are based on a Weibull k value of 2.0

Figure 1. Wind resource map for the United States.

As part of the CDEAC effort for the WGA, a set of wind supply curves was developed to estimate the potential for wind in the WGA footprint and to analyze the impact of available transmission on supply and cost [4]. In addition to the supply curve development for WGA, many regional and subregional transmission plans were used to get a better idea of potential wind development through 2015. Within the WGA footprint, studies have been performed that cover the Western Electricity Coordinating Council (WECC) by Seams Steering Group of the Western Interconnection (SSG-WI), Rocky Mountain Area Transmission Study (RMATS), and a project under way in the Northwest (Northwest Transmission Assessment Committee [NTAC]). For states outside the WECC, the Midwest Independent System Operator (MISO) considered wind development in the MISO Transmission Expansion Plan (MTEP) in 2003 [5] and has studied other scenarios in more recent MTEP analyses [6].

Additional work in the West has evaluated new innovative transmission tariffs that provide long-term transmission access on a conditional firm or nonfirm basis. The WTF concluded that such transmission tariffs could speed the development of wind and increase the efficiency of the transmission system. We developed three scenarios for 2015: (1) assuming little if any transmission tariff development, (2) a midrange of wind development according to the various transmission studies, and (3) a high-end wind development scenario. Figure 2 illustrates the range of these scenarios, and Figure 3 shows the approximate locations of this wind development in the West.

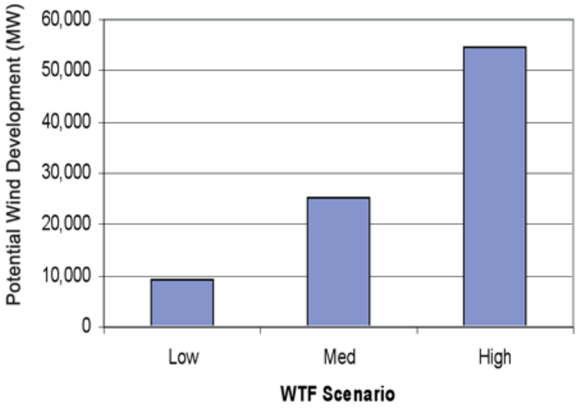
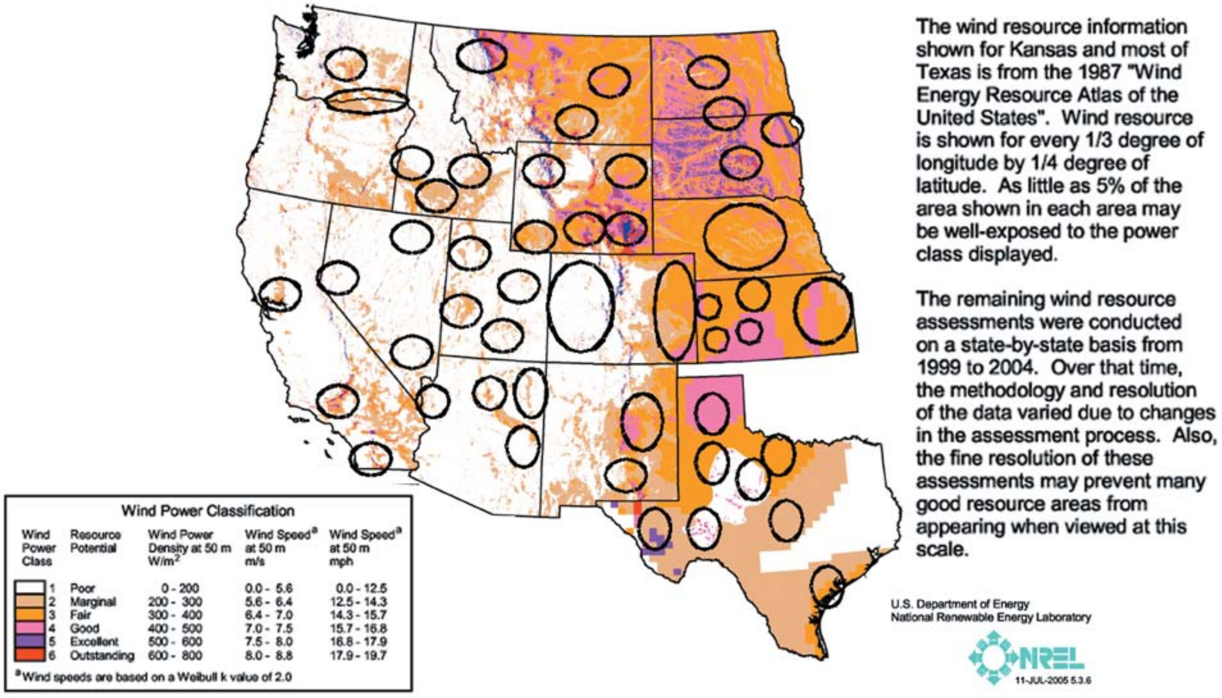


Figure 2. WTF wind development scenarios for 2015.


The wind resource information shown for Kansas and most of Texas is from the 1987 "Wind Energy Resource Atlas of the United States". Wind resource is shown for every 1/3 degree of longitude by 1/4 degree of latitude. As little as 5% of the area shown in each area may be well-exposed to the power class displayed.

The remaining wind resource assessments were conducted on a state-by-state basis from 1999 to 2004. Over that time, the methodology and resolution of the data varied due to changes in the assessment process. Also, the fine resolution of these assessments may prevent many good resource areas from appearing when viewed at this scale.

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s	Wind Speed[a] at 50 m mph
1	Poor	0 - 200	0.0 - 5.6	0.0 - 12.5
2	Marginal	200 - 300	5.6 - 6.4	12.5 - 14.3
3	Fair	300 - 400	6.4 - 7.0	14.3 - 15.7
4	Good	400 - 500	7.0 - 7.5	15.7 - 16.8
5	Excellent	500 - 600	7.5 - 8.0	16.8 - 17.9
6	Outstanding	600 - 800	8.0 - 8.8	17.9 - 19.7

[a] Wind speeds are based on a Weibull k value of 2.0

U.S. Department of Energy
National Renewable Energy Laboratory
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Figure 3. Wind locations for WTF high-development scenario, 2015.

We developed supply curves based on the GIS data represented in Figure 1. Not all land can be used for wind plant development, even though there may be a viable resource. Exclusions for urban areas, national parks and preserves, wilderness areas, and water were applied to the GIS data. The analysis converts wind speed to potential wind power using modern wind turbine characteristics and an average shear factor to account for the difference between the mapped wind speed and the assumed turbine hub height. An area with a high average wind speed would have a lower energy cost than an area with a low wind speed. It is likely that the mapping database misses some high quality wind locations, which would result in more supply of wind at a lower cost than what is shown here. Table 1 shows the base data for the supply curve development. Costs do not include the PTC, which would reduce the effective cost of energy.

For this analysis, we developed several sets of supply curves for each state and then combined them for the entire country. Each supply curve is based on an assumption concerning how much of the existing transmission grid is available to transport wind. The first assumption is that no existing transmission is available, requiring wind to pay to build all of its own transmission. The subsequent cases assume that 10%, 20%, 30%, or 40% of the existing grid is available to transport wind. If the wind generation uses up all the available transmission capacity, new transmission is "built" to the nearest load center(s). Because the GIS database includes transmission locations and line ratings, we could simulate building new transmission to connect the wind plant to the existing grid. For each load center, we limited wind energy as a percent of the total to 20%. Once we reached this limit, we "built" additional transmission to the next nearby load center at a cost of $1,000/MW-mile.

Figure 4 shows the supply curves for the entire United States. The supply curve on the far left is the case of no available transmission for wind, and the supply curve on the far right is the wind supply assuming 40% of existing transmission is available for wind.

Table 1:
Wind levelized cost of energy and capacity factor by wind power class.

Wind Power Class	Wind Speed @ 50 m	Capacity Factor	Nominal LCOE
3	6.4-7.0	30.0	.0744
4	7.0-7.5	33.8	.0659
5	7.5-8.0	39.8	.0537
6	8.0-8.8	43.6	.0490
7	8.8-11.1	49.6	.0431

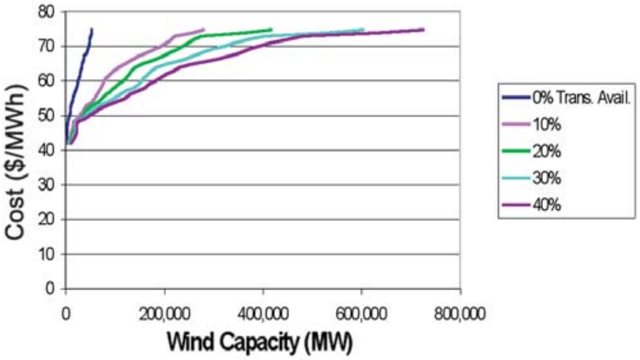

Figure 4. Supply curves with alternative assumptions for the percentage of existing transmission that is available to transport wind to load.

Because some of the detail is difficult to discern in the graph, Figure 5 shows an inverted supply curve as discrete points. To further expand the view over the lower wind costs, Figure 6 zooms in further.

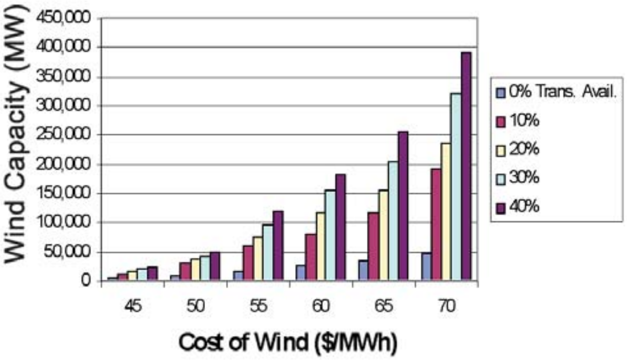

Figure 5. Impact of transmission availability on wind supply.

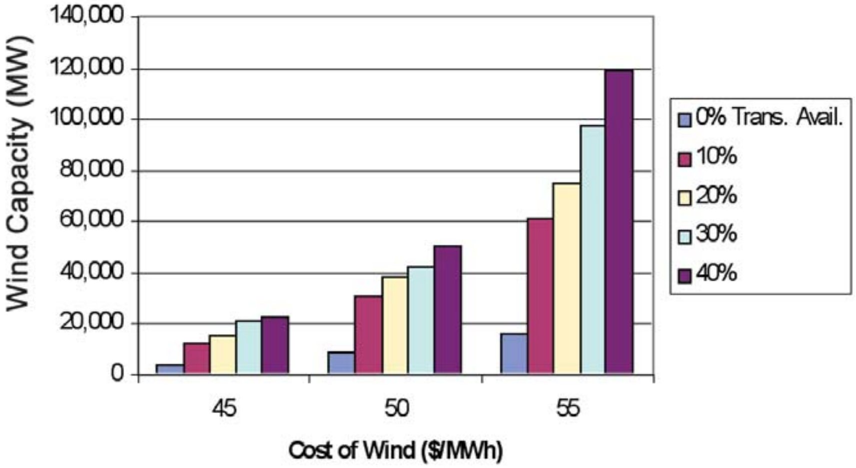

Figure 6. Zoom of Figure 5 at lower cost of wind energy.

The U.S. Department of Energy Wind Program has developed a set of cost goals for technology development. For wind class 6, the levelized costs of energy targets from 2010 to 2050 are shown in Figure 7. The cost of wind energy in lower wind speed locations is also expected to improve, and the Wind Program is developing low wind speed technology that is expected to allow the use of less energetic sites that are closer to transmission and load centers. Because the supply curves shown in Figure 4 are based on current technology and wind speed at 50 meters, these supply curves underestimate the potential for wind.

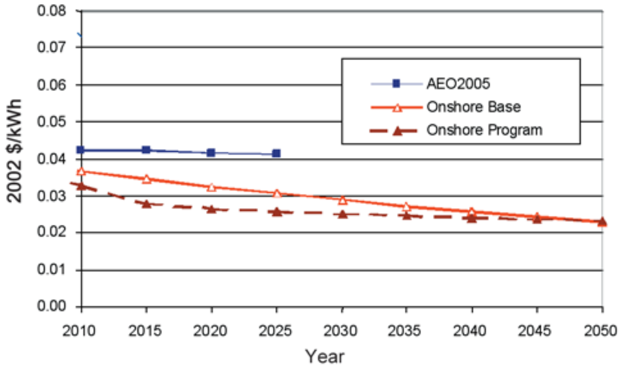

Figure 7. Projected wind energy cost decline from 2010 to 2050 for class 6 wind sites. The lower red curve (Onshore Program) denotes the low-wind speed turbine (LWST)/Wind Program goal to reduce costs. The Onshore Base red curve is the "base case" without the LWST.

We developed a high-penetration market simulation based on the Wind Deployment System model, currently under development at NREL [7,8]. This model represents the U.S. power grid by control area (balancing authority), uses and projected wind costs shown in Figure 7, and GIS representations of wind and transmission. The model contains generation from all technologies along with price forecasts and competes resources based on cost to determine the least-cost national portfolio that will successfully meet demand and energy requirements.

A key assumption used for this scenario is that the PTC is renewed until 2010, followed by a smooth phase-out until 2030. The base simulation results in approximately 20% of U.S. energy consumption served by wind. The results of this simulation were adjusted to account for energy efficiency improvements, and the wind capacity and energy is lower in absolute terms than the base case, but the annual energy from wind is maintained at 20% of U.S. energy. The results of the simulation are shown in Figure 8.

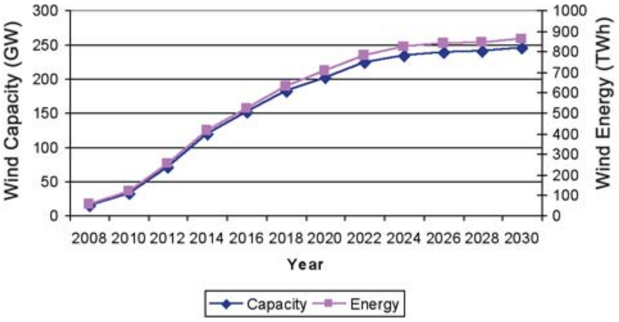

Figure 8. Results of high-penetration wind market simulation.

To assess the carbon reduction potential, the wind capacity from the market simulation was converted to annual energy. Because different regions of the country have significant differences in generation fuel mixes, quantifying the carbon reduction potential from wind is not straightforward. Figure 9 shows the relationship between wind energy generation and carbon reduction using several carbon displacement rates—260 metric tons per GWh, 210 metric tons per GWh, and 160 metric tons per GWh. The last rate may be more reflective of fuel displacement that includes fuels other than just coal, although a more rigorous analysis is required to obtain a more accurate estimate of carbon reduction.

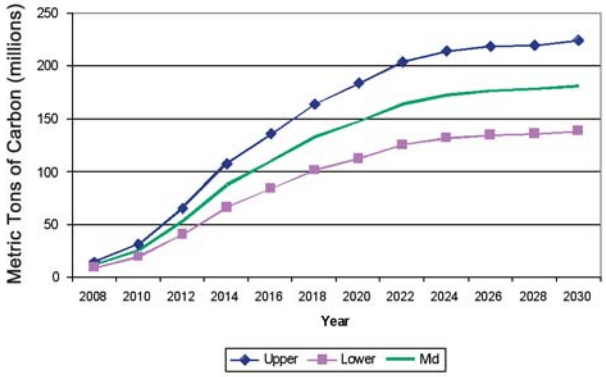

Figure 9. Range of annual carbon reduction from wind.

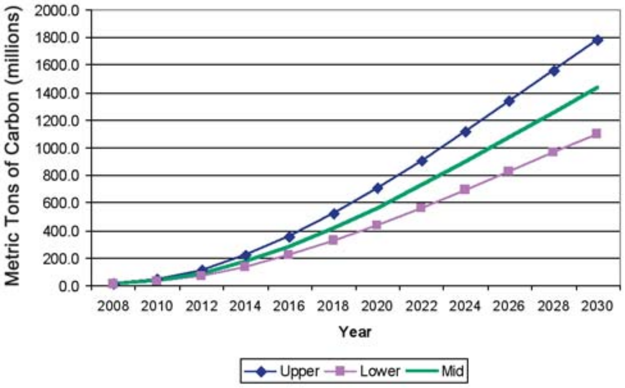

Figure 10. Range of cumulative carbon reduction estimates through 2030.

The precise location of these wind power plants cannot be known in advance. However, Figure 10 represents the cumulative carbon displacement for the carbon reduction rates discussed previously.

It is reasonable to assume that the wind development would occur near available transmission and at high-quality wind locations. Figure 11 is from the wind penetration case illustrated above, but before energy efficiency improvements are considered. Therefore, this map is generally illustrative of where wind development could occur, but should not be treated as a precise estimate.

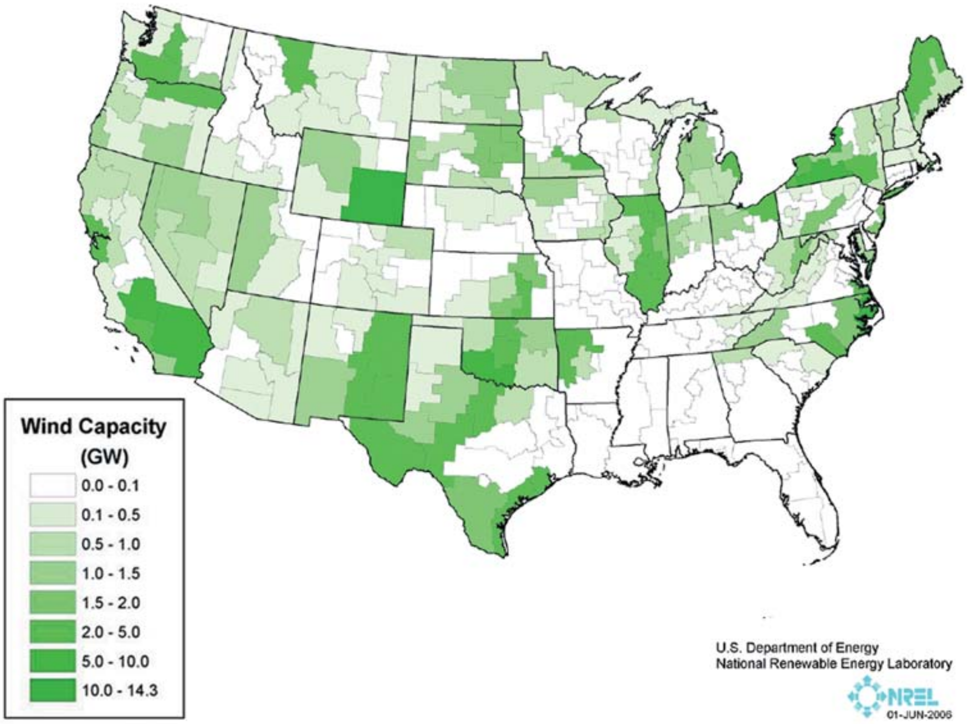

Figure 11. The WinDS model scenario of approximate wind locations with 20% penetration of electric grid (energy).

Conclusions

The potential for wind to supply a significant quantity of energy in the United States is enormous. This implies a significant potential to reduce carbon emissions by displacing other fuels. Although a more detailed analysis would be helpful, we estimate that the widespread use of wind power will result in the cumulative avoidance of 1,100 to 1,780 million metric tons of carbon by 2030.

This study shows the importance of transmission availability on wind supply. Detailed transmission studies with appropriate data sets are required to more fully assess this issue for specific deployment options, but clearly, availability of transmission capacity helps large-scale deployment by reducing the cost of delivered wind energy.

Because wind transmission does not require firm transmission rights, alternative transmission tariffs can make more effective transmission available for wind delivery. This may imply greater wind development than if traditional transmission tariffs are applied to wind generation, which will help with carbon mitigation.

Aside from the supply curves, there is additional empirical evidence of a potential large-scale expansion of wind that comes from utility IRPs, state RPS requirements, and large-scale transmission studies in the West and the Midwest.

Continuing declines in the cost of wind generation will increase wind development. The recent cost increases may be temporary but may also signal an upward trend in wind turbine prices. In addition, GIS data used for this supply curve analysis may significantly underestimate the supply of wind in the West.

Acknowledgements

Thanks to Donna Heimiller and George Scott, National Renewable Energy Laboratory, for their excellent support of the supply curve development, and to NREL’s Nate Blair, Maureen Hand, Alan Laxson, and Walter Short for the use of their market analysis results and WinDS.

The Wind Task Force report of the CDEAC can be found at http://www.westgov.org/wga/initiatives/cdeac/Wind-full.pdf

Information on the WinDS model can be found online at http://www.nrel.gov/analysis/winds

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Tackling Climate Change in the U.S.

Potential Carbon Emissions Reductions from Biomass by 2030

by **Ralph P. Overend, Ph.D.** and
Anelia Milbrandt
National Renewable Energy Laboratory

Warren Gretz, NREL PIX 08369

Energy crops such as the switchgrass shown here can fuel base load biomass power plants and help revitalize rural economies.

Biomass can contribute to climate change mitigation by offsetting the use of fossil fuels in heat and power generation and by providing a feedstock for liquid fuels production.

Biomass can contribute to climate change mitigation by offsetting the use of fossil fuels in heat and power generation and by providing a feedstock for liquid fuels production. In addition, there is the complementary potential for carbon sequestration in the soil (using agronomic and silvicultural practices to promote soil carbon accumulation) and in the capture and sequestration of carbon during the processing of biomass. We describe these three options as offset, soil carbon sequestration, and carbon capture and sequestration (CCS).

Two key studies provide a first level estimate of the "economically" accessible biomass contribution. The first is known as the "Billion Ton Study," a collaborative effort among the U.S. Department of Energy (DOE), the U.S. Department of Agriculture (USDA), and the national laboratories led by the Oak Ridge National Laboratory [1] .This study estimates a potential 2025 crop and biomass residue contribution of 1.26 billion metric tons (gigatons or Gt). (Note that unless otherwise noted, all biomass is described on a dry basis.)

The second is the Western Governors' Association (WGA) Clean and Diversified Energy Study by the Biomass Task Force. This study generated an electrical energy supply curve for the WGA 18-state region that identified slightly less than 50% of the region's technical potential as being economically accessible to generate 120 terawatt-hours (TWh) of electricity at less than $80 per megawatt-hour ($/MWh).

Biomass Carbon Offset Potentials

The carbon offset achievable for biomass depends on the energy system that the biomass-based system is replacing. It is self-evident that a biomass system that replaces a coal-fired electricity generation system with equal efficiency will offset the entire fossil carbon budget. However, replacing a natural gas-fired electricity system with a lower efficiency biomass system offsets much less fossil carbon per unit of land.

The European well-to-wheels study [2] illustrated this by calculating the annual carbon dioxide offset from a hectare of land for a number of systems, including high-yielding lignocellulosic crops such as short rotation woody crops (SRWC) like willow or poplar and herbaceous energy crops (HEC) like switchgrass and miscanthus, as well as more common agricultural crops. The abbreviations in Table 1 are integrated gasification combined cycle (IGCC), pulverized coal (PC), internal combustion engine (ICE), fuel cell vehicle (FCV), and fatty acid methyl esters (FAME).

Many studies have observed relatively high yield of CO_2 for fossil electricity production offsets relative to those for transportation uses of biomass. Recent work [3] also demonstrates the net energy improvements of using lignocellulosics rather than cereal food crops for transportation applications.

Table 1.
Effective carbon dioxide offsets of one hectare of land under different crop yield and process efficiency options.

Biomass System	**Fossil fuel offset**	**tCO_2/ha/yr**
Lignocellulosic crop - IGCC - electricity	coal - PC boiler	23.0
Lignocellulosic crop - compressed H_2 - central plant + fuel cell vehicle (FCV)	Petroleum driven ICE	17.0
Lignocellulosic crop - comp H_2 on-site FCV	Petroleum driven ICE	14.5
Lignocellulosic crop - fluid bed combustor steam cycle to electricity	coal - PC boiler	14.0
Lignocellulosic crop - IGCC - electricity	Natural Gas CC	10.5
Lignocellulosic crop - comp H_2 central ICE diesel ICE	Petroleum driven ICE	8.5
Lignocellulosic crop - to ethanol in ICE	Petroleum driven ICE	4.0
Cereal crop (wheat) - to ethanol in ICE	Petroleum driven ICE	3.0
Oilseed (soya, rape) to FAME in ICE	Petroleum driven ICE	2.0

Soil Carbon Sequestration

The biomass used in offset applications is generally above-ground biomass. Below ground there is an accumulation of root mass, and the biomass that falls on the soil surface—described as litter—is also partially taken into the soil through the action of micro-organisms, insects, and earthworms. The below-ground carbon is actively used by micro-organisms, but a portion of the soil organic matter becomes relatively inert and stays in the soil over long time periods [4].

Quantification of the transformation pathways and residence times of carbon in soil are subjects of intense study to clarify the role of soil carbon in climate change mitigation [5,6,7]. Changes in agricultural practice such as no-till agriculture, which eliminates soil disturbance by plowing and cultivation, also impact the ability of soils to fix carbon under different cropping regimes [8]. Typical rates of carbon fixation are on the order of 200 to 500 kilograms of carbon per hectare per year (kgC/ha/yr) compared with offset rates from Table 1 for power systems on the order of 4 to 6 metric tons per hectare per year (tC/ha/yr).

Carbon Capture and Sequestration (CCS)

Biomass also offers one carbon mitigation option that is quite different from the other renewable energy sources. Plants capture carbon through photosynthesis, and that carbon becomes a component of biomass, effectively functioning as a sequestration strategy by withdrawing carbon from the atmosphere.

There are two ways to accomplish this. The first is to combine biomass and fossil feedstocks in an advanced conversion process plant (to generate fuels and/or electricity); capture carbon dioxide by chemical means; and then compress and store it in aquifers, deep strata, or the ocean [9]. Such CCS plants are already under investigation [10] and would be an integral part of a future hydrogen economy using carbonaceous fossil resources.

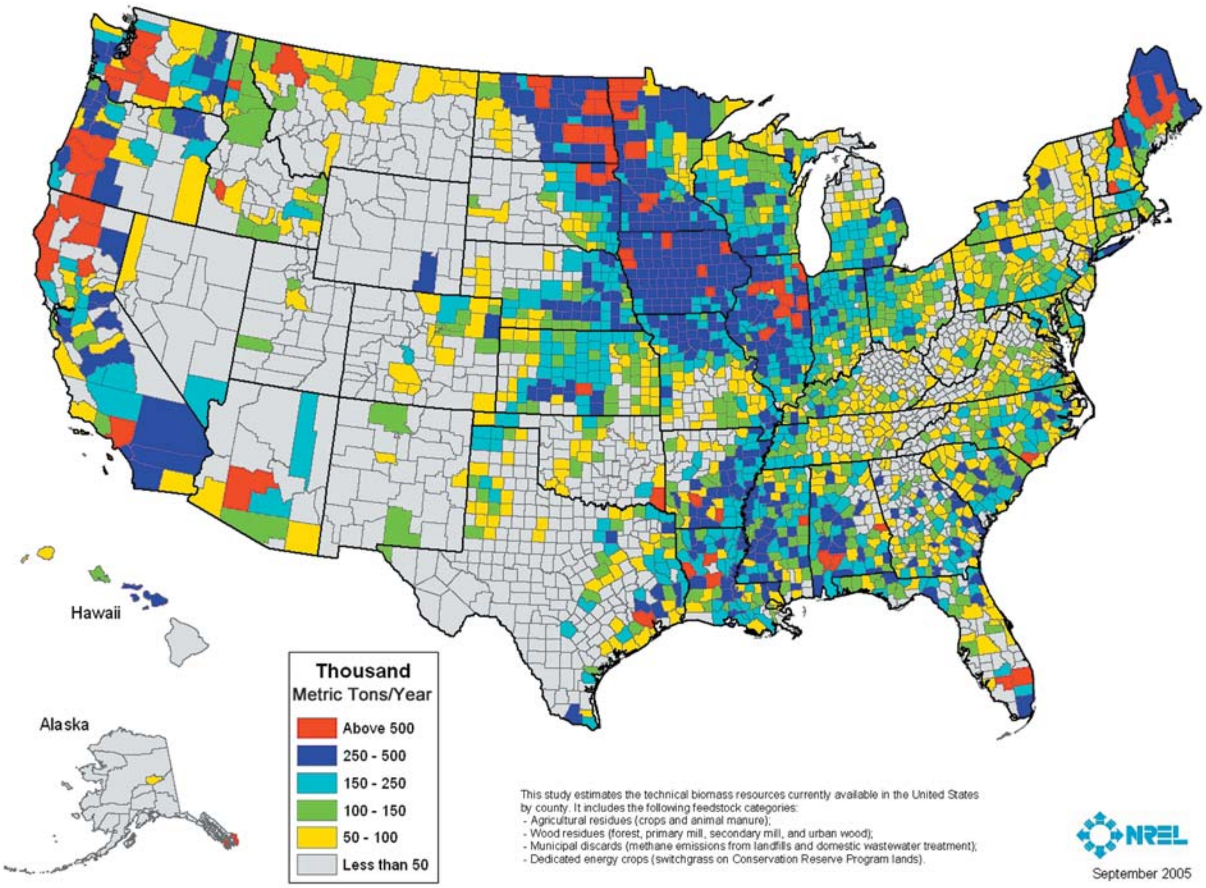
A more novel form of CCS would arise in pyrolysis processes in which liquid and gaseous fuels are produced along with a char residue [11]. In the humid tropics of Brazil, there is a sustainable agriculture based on the incorporation of char or charcoal into the otherwise infertile soils. The soils are black because of the high carbon content, hence their name Terra Preta (black earth). These soils also contain pre-Columbian artifacts that researchers have carbon-dated to 1775 years ago [12]. Because char residue from pyrolysis processes would contain about 10% of the original carbon, the carbon storage component that would arise from the incorporation of the char into soils would likely be about 1 tC/ha/yr, compared with offset rates from Table 1 for power systems on the order of 4 to 6 tC/ha/yr.

Current Biomass Use for Energy (Bioenergy)

For the entire world, the current primary energy consumption is about 427 quads. About 10% of the primary energy input is biomass [13] and at least two-thirds of that is used in developing countries in relatively inefficient and high emissions-producing cooking and heating applications. This latter application is sometimes described as traditional biomass, and the uses that are more common in industrial countries—ranging from combined heat and power (CHP) to transportation fuels—are described as modern biomass.

The total worldwide biomass electrical capacity is on the order of 40 gigawatts (GW)—about one quarter of which is in the United States—and is growing at a rate of about 3% to 4% per year. Transportation fuels are mainly ethanol produced from sugar crops and cereals, with a modest contribution of biodiesel from the fatty acid methyl esters (FAME) produced from triacylglycerides (TAG) in the oil seed crops soya and rape. The current global growth rate for biomass-based transportation fuels is more than 10% per year because of the current high crude oil prices. The major bioenergy application is still process heat.

The Billion Ton Study has identified more than 1 gigaton of resources, which could ultimately offset more than half of today's oil imports.



This study estimates the technical biomass resources currently available in the United States by county. It includes the following feedstock categories:
- Agricultural residues (crops and animal manure);
- Wood residues (forest, primary mill, secondary mill, and urban wood);
- Municipal discards (methane emissions from landfills and domestic wastewater treatment);
- Dedicated energy crops (switchgrass on Conservation Reserve Program lands).

September 2005

Figure 1. Distribution of biomass resources available by county in the United States [19].

DOE and the USDA have allocated significant resources over the last 3 decades to emerging technologies for using energy crop systems. This effort is just now reaching commercial application [14]. Current bioenergy programs are targeted at available resources, which include the residues from urban centers, agricultural residues such as wheat straw and corn stover, forest residues from harvesting and forest health operations, mill and process residues such as sawdust, pulping liquors and residues from food processing and animal husbandry.

These resources are well-illustrated in the recently published National Renewable Energy Laboratory (NREL) atlas of biomass resources [15]. Figure 1, taken from the atlas, shows the county level resource technical potentials for all of the above biomass resources. The density is highest in the corn belt and in urban centers.

In addition, the Billion Ton Study mentioned previously has identified more than 1 gigaton of resources, which, if converted to liquid fuels, could ultimately offset more than half of today's oil imports [1].

Converting the resource base into a potential supply curve for a biomass product such as electricity or a liquid fuel has not been undertaken very often. However, there are many studies of the supply curves for the delivery of a raw biomass feedstock to a central location for processing as in the SHAM model from Nilsson [16]. From these studies, we can derive a broad array of the factors affecting the final cost of product. The two most important factors today are the annual yield of biomass per unit area and the efficiency of the process of converting the biomass to the final energy product.

Biomass productivity per unit area affects the radius from which the bioenergy crop has to be harvested and then transported to the central facility. The process efficiency determines the total amount of biomass required to be transported to the facility for a given output.

Table 1 illustrates both of these factors in the results drawn from the well-to-wheels life cycle assessment methodology [2]. A high yield is typified by the lignocellulosic crop in the table, which can be compared with relatively low-yielding oil seeds in the FAME production. The high process efficiency of the hydrogen from syngas to a fuel cell vehicle end use can be compared with the effect of the lower efficiency Fischer-Tropsch liquids (FTL) production for use in an ICE vehicle.

In Table 2 below, the effect of yield and conversion efficiency is illustrated in terms of the percent of the land area inside a 50-kilometer (km) radius circle that would need to be harvested annually for different crop productivities ranging from dryland wheat straw with a low productivity of about 3 t/ha/yr to a future high yielding lignocellulosic crop with about 18 t/ha/yr dry matter production. The effect of efficiency is identified with a low-efficiency case (1990 to 2000 technology) and a high-efficiency case for about 2015, for three levels of process plant scale based on feedstock inputs of 500, 2,000, and 10,000 t/day respectively.

In the delivery of the biomass to the processing plant, there are three major cost centers:

Table 2:
Percent of the area of an 80-km radius circle needed to provide biomass at scales of 500 to 10,000 metric tons per day for different biomass productivities. Areas are given in thousands of hectares (kha)

Yield t/ha/yr	**500 t/day** **kha**	**% A**	**2000 t/day** **kha**	**% A**	**10,000 t/day** **kha**	**% A**
3.3	44.5	2.2	178.0	8.8	891	44.30
9.0	16.3	0.8	65.3	3.3	327	16.30
18.0	8.2	0.3	32.7	1.6	163	8.13

Table 3.
Representative yields of bioenergy products for different scales of production using current (2000) technology and future (2015) efficiencies of conversion.

Yield t/ha/yr		**500 t/day**		**2000 t/day**		**10,000 t/day**	
Conversion	**Units**	**2000**	**2015**	**2000**	**2015**	**2000**	**2015**
Electricity	MW	30.4	45.6	121.0	182.0	607	911
Ethanol	kL/day	166.0	187.0	663.0	746.0	3,317	3,732
Fischer-Tropsch liquids	Bbl/day	453.0	538.0	1,814.0	2,154.0	9,069	10,770
Hydrogen	t/day	6.5	7.7	25.9	30.8	130	154

The lowest levelized cost of energy is for larger plants with biomass resources that are harvested at high yields.

planting and management (including where necessary irrigation costs), harvesting, and transportation from the field or forest edge to the processing plant. Current energy crops cost between $20 and $60/t delivered.

Research is focused on the optimum form of the biomass harvest. Today, there is a lot of cost associated with adapting the harvest systems of food and fiber production systems to the bioenergy application, which is less restrictive on the physical morphology of the product. For example, one concept would be to make the harvested material more dense prior to transportation, because typical agricultural bale densities are such that current vehicles are volume-limited. Such a strategy would increase the vehicle payload.

Many of the biomass conversion processes are maturing rapidly. Conversion to heat, for example, is often at efficiencies as high as 85% to 90%. Today's electricity systems are capable of more than 30% efficiency, and analysts predict that future gasification-based integrated gasification combined cycle (IGCC) will be at about 45% [17]. In the case of lignocellulosic conversion to ethanol using current enzymatic hydrolysis, the yield is about 60 to 65 U.S. gallons per metric ton, while the future technology forecast is for 90 U.S. gallons [18].

The cereal starch-to-ethanol industry has been developing for over 30 years, and in that time has reduced the investment cost per annual U.S. gallon (1 U.S. gallon = 3.785 liters) from more than $3/U.S. gallon per year (g/yr) to about $1.30 g/yr, while yields have improved from 2.3 gallons per bushel (g/bu) to 2.8 g/bu. This latter improvement has its origins in both process and crop improvements. The energy consumption per unit of output has fallen by over 70% in the same time. The sugar cane-to-ethanol industry has demonstrated very significant learning curve effects as well [19].

Supply Curve Development

Traditionally, a supply curve—a plot of cost per unit of output ($/MWh of electricity or $/liter of transportation fuel) against the cumulative output—would be generated for a specific plant location, and the size of the plant would be determined by the output below some cost threshold. Because the plant location and the potential biomass resource generation locations would be fixed, the actual road network would be used for the logistics. Likewise, the farm or forest production costs would be based on best practice in the region, taking into account the local climate and soil determinants of plant productivity. At the conversion process plant, the investment cost and those of the fixed and variable operating costs would be determined from vendor quotes.

NREL was a member of a group working on the estimation of a supply curve for the 18 western states for the WGA Clean and Diversified Energy Initiative (CDEAC) [20], in which a series of approximations were used to derive a supply curve for the region. The working group used the best available data sources on quantity, quality, environmental constraints, and cost of agricultural, forest, and urban biomass resources.

Efficiency increases in the use of spent pulping liquor (black liquor) may also contribute to increased generating capacity from biomass, but good data are currently lacking and this resource was not included in the estimate. Dedicated crops are also not included in the base resource estimate described here, because they do not currently contribute substantial amounts of biomass in the WGA states. At this stage of their development, dedicated crops could be considered to be equivalent to a high yield of agricultural residue, and their planting would, in effect, displace agricultural crop plantings generating residues in specific areas.

The California Biomass Collaborative compiled a database containing over 170 million dry metric tons equivalent of biomass for the WGA area [21]. At a nominal 30% conversion efficiency and a 90% capacity factor, this corresponds to 32 GW of biomass generation. The major data sources are detailed below.

Agricultural Residue

Agricultural crop residues are lignocellulosic biomass that remains in the field after the harvest of agricultural crops. The most common residues include stalks and leaves from corn (stover) and straw from winter and spring wheat production. Biomass resource estimates have so far been developed for all WGA states only for field and seed crops and animal manures. Data for orchard and vineyard residues, vegetable crop residues, and food processing residues (not including waste water from food processing operations) were included from the recent biomass assessment conducted for California [21], but similar resource estimates have not yet been made for the other states. For this assessment, field crops include only wheat and corn residues estimated according to the methodology of Nelson [22] with the exception of the addition of rice straw in California. Agricultural crop residues play an important role in maintaining/improving soil tilth, protecting the soil surface from water and wind erosion, and helping to maintain nutrient levels.

Although agricultural crop residue quantities are substantial, only a percentage of them can potentially be collected for bioenergy and bioproduct use primarily due to their effect on soil productivity and, especially, soil erosion. The amount of soil erosion agricultural cropland experiences is a function of many factors, including crop rotation, field management practices (tillage), timing of field management operations, physical characteristics of the soil type (soil erodibility), field topology (percent slope), localized climate (rainfall, wind, temperature, solar radiation, etc.), and the amount of residue (cover) left on the field from harvest until the next crop planting. Nelson [22] provided state-level supply curves expressed in terms of total dry tons available at the field edge at a given price over nine different price levels ($12.50 to $50.00 per dry ton) for 16 of the 18 states in the WGA region. These values were estimated using National Agricultural Statistics Service corn and wheat production data for 2000-2003 and a procedure that estimates crop residue retention levels after harvest from continuous corn- and wheat-based rotations subject to three different field management (tillage) scenarios: conventional tillage (CT), conservation/reduced tillage (RT), and no-till (NT) such that rainfall and/or wind erosion rates did not exceed Natural Resources Conservation Service soil-specific tolerable soil loss limits. County-level supply curves at each of nine price levels were arrived at by assuming that residue quantities available at any one of the nine price levels were proportional on a percentage basis to the four-year average (2000-2003) corn or wheat production level in that particular county.

Forest-Derived Biomass Resources

Ken Skog and Jamie Barbour, U.S. Forest Service, prepared the databases for the WGA Biomass Task Force forestry analysis. The data are primarily for timberland, which is forest land that has not been withdrawn from timber use by statute or regulation and is capable of producing 20 cubic feet per acre per year of merchantable wood in natural stands. We obtained information about the materials available from current timber operations both in the forest (unused logging slash, for example) and at the processing mills (mill residues, including sawdust) from the Timber Products Output interactive web assessment tool maintained by the U.S. Forest Service [23].

We made the estimates of wood biomass that may be supplied annually for fuel from timberland and other forest land based on selected assumptions about treatments. Timberland and other forest land area in the 16 western states amounts to 141 million acres and 80 million acres, respectively. We used two sources for biomass supply estimates from timberland, the Fuel Treatment Evaluator (FTE) 3.0 [24] and the DOE/USDA billion ton supply report [1]. The Billion Ton Study estimates the wood biomass supply that may be removed from timberland areas that have a higher density of trees and would benefit from thinning, including areas that are and are not currently at high risk for stand replacement fire at 10.8 Mt/yr. The FTE 3.0 estimates supply from treatments focused on areas currently at high risk for stand replacement fire at 6.2 Mt/yr. The FTE 3.0 estimate would treat a subset of the area identified for treatment by the Billion Ton Study.

Urban Residues (Municipal Solid Waste [MSW])

Values for biomass in MSW were available for California at the county level [21], and we obtained data for the remaining states (with the exceptions of Alaska and Montana) from a recent survey of state solid waste and recycling officials [25]. We calculated a value for annual per capita MSW generation of 1.38 metric tons per person per year from the data available for the 16 states. We applied this annual per capita factor to the populations of Alaska and Montana to estimate their MSW generation. We applied values for moisture content (30% wet basis) and biogenic fraction of MSW (56%) to the MSW values to arrive at estimates of biogenic dry matter in MSW for each state.

This resource includes only the biomass component of MSW and not the entire MSW stream. The biomass component consists of paper and cardboard, green waste, food waste, and construction wood waste, and specifically excludes plastics, tires, and other non-biomass materials. We determined biomass in MSW diverted from landfill by subtraction of disposal from generation.

Landfill Waste in Place (Landfill Gas-to-Energy)

Data on the amount of waste currently in place in landfills in the WGA region were obtained from the U.S. Environmental Protection Agency's Landfill Methane Outreach Program [26]. Data for individual landfills were aggregated at the county level.

Logistics Model

It was not feasible to conduct a search of each county to locate the resources, power lines, and substations in order to optimize the transportation costs of moving the harvested/collected biomass to the conversion plant and transmitting the electricity to the grid.

To facilitate the analysis, we used a simple logistics model [27] that assumed that the resource area was contiguous (even though this is not always true). We estimated the fraction of the land area devoted to the resource from the area planted with the crop(s) chosen (wheat and corn) relative to the total land area (arable land, for example). The county level productivity per unit area of the crop was then used to compute the total metric ton/km transportation effort required.

For agricultural land, the assumption was of a plant centrally located in the arable land area. For forest crops, the conversion plant was assumed to be at the center of the diameter chord for a semicircular collection area. The winding factor of the terrain was assumed to be 1.41 for essentially flat farmland or urban residue collection areas, and 1.8 or 2.0 for mountainous forest lands.

For solid fuels, truck transport is the dominant method of feedstock transport. Barge or train transport is currently used only in a very few instances. Basic truck transport cost functions are known from data in the Statistical Abstract of the United States (1997), in which the total outlay for local transportation was $122 billion in 1996. Local trucking (non-intercity) ton-miles logged were 506 billion in 1996. This implies a national average local freight charge per ton-mile of approximately $0.24. The Billion Ton Study assumed that the range of transportation costs associated with forest biomass removal was $0.20 to $0.60 per dry ton-mile. This equates to $0.10 to $0.30 per green ton-mile. For the base case analysis, we used a value of $0.20 per ton-mile.

Cost of Harvest and Collection of Materials Prior to Transportation

The corn stover and wheat straw data included the cost of agricultural residues to the field edge. For the forest materials, we assumed a cost of $20/t dry basis for the fuel materials. This implied in timber treatments that a subsidy was available to reduce the cost of fuel treatment to that level. For forest slash, the assumption was that the bulk of the harvest cost was borne by the primary lumber or pulp harvest. We assumed the same $20/t dry basis for the urban residue stream as the cost of the material at the materials recovery transfer station. We assumed that landfill gas has zero collection cost, because it would have been recovered as part of greenhouse gas mitigation even if there had been no productive use.

Conversion Technologies and Applications

An overarching view of biopower production can be organized into a primary conversion process that converts the biomass into an intermediate product (heat or fuel gas) that is then converted into electricity. While there are a large number of potential process configurations, we decided that we would input a small subset consisting of the following to the supply curve analysis, by means of analytical functions that relate the heat rate (efficiency), capital investment (CAPEX), and operating and maintenance costs (O&M, fixed and variable):

- Stoker and fluid bed combustors with steam generation and steam turbines
- Gasification with applications to boiler steam generation and steam turbines,

combined cycle (gas turbine, heat recovery steam generator, and steam turbine), or an ICE
- Anaerobic digestion (animal, water treatment, and landfill) with ICE or gas turbine.

While the CDEAC Biomass Task Force recognized that CHP applications at industrial or institutional sites can benefit from the high overall efficiency achievable, it was not possible to estimate the extent of such deployment. When the CHP-using industry also produces a portion or all of its fuel as a byproduct, as in today's forest industries, this application is very economical.

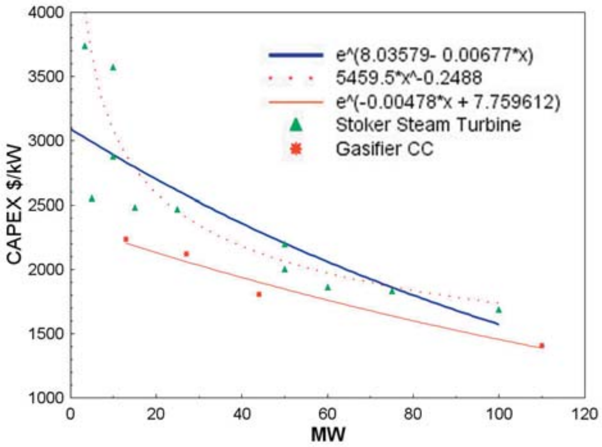


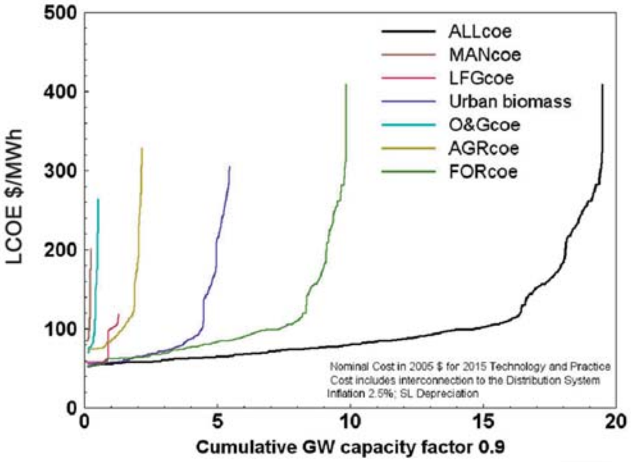
Figure 2. Correlation of capital cost (2005 dollars) for technologies generating steam for electricity generation. The curve for IGCC reflects the much higher efficiency of electricity generation over a regular stoker or fluid bed fired boiler and Rankine cycle.

An extensive discussion of the parameters for the analytic equations for each of the candidate technologies is given in the Biomass Task Force Report: Supply Addendum [20].

Determining the Cost of Electricity

For each supply resource, we calculated the cost of harvest/collection, transportation, and conversion technology in the complete chain from plant to electricity as the levelized cost of electricity (LCOE). We used the NREL methodology [28] with discount factors and inflation factors supplied by the WGA as described in the CDEAC guidance documents (Quantitative Work Group Guidance to Task Forces of the WGA's CDEAC, Version 1.6 July 12, 2005). We further assumed that the maximum scale of a biomass facility (either stoker combustor or IGCC) would be 120 megawatts (MW). We assumed that units that were below 60 MW would be connected to the local distribution grid at local substations, while the larger size units would be connected to the high-voltage distribution grid via substations. For counties with biomass supplies greater than the largest plant size, we created multiple plants to use up the available supply. For any given resource supply and cost, the generation technology selected was the one that resulted in the lowest-cost outcome. For larger sizes, this tended to be the IGCC; for the smaller units (less than 15 MW_e), the technology would either be a stoker steam turbine or a gasifier/ICE combination.

We summarized the final base case for all of the resources in the supply curve shown in Figure 3.



Nominal Cost in 2005 $ for 2015 Technology and Practice
Cost includes interconnection to the Distribution System
Inflation 2.5%; SL Depreciation

Figure 3. Final WGA 2015 biomass supply curve for the 18 western states consisting of 15 GWe at less than $80/MWh. Key to figure curves: Man = Manure, LFG = Landfill Gas, Urban Biomass = Municipal Solid Waste, O&G = Orchard and Grapes (California only), AGR = Agricultural Residues, FOR = Forestry Resources.

The 15 GW_e corresponds to 31 million metric tons of carbon (MtC) annual displacement using a conversion of 260 tC/GWh. Assuming that the same feedstock had gone into the production of Fischer-Tropsch naphtha, the annual carbon offset from the daily production of 200,000 barrels (Bbl) would be 8.3 MtC using a conversion of 3 kilograms of carbon per U.S. gallon of gasoline (see Table 4).

Extrapolation from the 170 Mt of biomass in the WGA study to the 1.26 Gt of biomass in the Billion Ton Study (see Table 4) is likely to underestimate the entire U.S. contribution in 2015. The urban contribution is likely to be much greater in the non-WGA regions as a result of the higher population density. Thus the estimates in Table 4 are almost certainly low. It should also be noted that the electricity and liquid fuels cases are presented only as either/or scenarios. The actual situation would be a mixture and would be compounded by technology options that are described as biorefineries that would both produce liquid fuels and—in addition to satisfying all of their internal CHP needs—export electricity.

Table 4.
Summary of U.S. 2015 electricity and transportation biomass offsets along with their carbon offset values.

Scenario	Energy Offset	Units	Carbon Offset	Units
Electricity	111.0	GW	230	MtC
Nathpha	1.5	MBbl/day	62	MtC

Deployment Versus Time

The annual deployment will be very dependent on government policy. Already there are significant policies, such as the renewable fuels standard, that effectively mandate set levels of fuel production out to 2012 in terms of ethanol equivalent output. Various states also have renewable portfolio standards (RPSs) that address the electricity system. Under RPSs, the deployment rates for biomass has been relatively slow with the exception of landfill gas-to-electricity schemes.

Ongoing studies with dynamic modeling of investor behavior in the liquid fuels arena suggest a very strong role for energy prices in determining the rate of capital formation in the liquid fuels arena [29].

Conclusions

Although the overall biomass estimate for the WGA region was 170 Mt of dry material capable of generating 32 GW, the supply curve demonstrates that over 50% of the total resource is likely to be economically inaccessible at more than \$80/MWh. A significant fraction of the agricultural residues did not qualify in the assessment due to the type of constraints described for the crops above. Many forestry areas did not reach the minimum size to feed any scale of plant. Examination of the curve shows that the lowest LCOE is for larger plants with biomass resources that are harvested at high yields. As we expected, the steep climb of the cost curve is associated with smaller plants and low area densities of biomass.

For the rest of the United States, applying the same proportional relationship suggests that, of the 1.25 Gt capable of generating 235 GW, only 110 GW would be economically available.

There are many technical factors that can significantly change this estimate. Conversion technology improvements in efficiency result in the horizontal axis of output (as GWh or Bbl/day) curve expanding. Advances in crop yield and reductions in harvest, collection, and transportation costs of biomass will result in a direct reduction in the LCOE as will reductions in the capital investment per unit of output.

Indirect effects will also be important in increasing the available biomass from a given area of land. A shift from the residue collection of annual row crops such as corn stover to annual harvests of perennial crops such as switchgrass will result in reduced concerns about soil erosion by water and wind. Likewise, crop production strategies that move from plowing and seeding to no-till agriculture for corn production would increase the fraction of the residue (corn stover) that can be environmentally harvested. Even changes in food production strategies—such as the worldwide reductions in crop subsidies that are envisaged as part of the World Trade Organization-Doha round—could influence the amount of available biomass. In Europe, this is already leading to discussions of decreasing food production area in favor of energy and industrial crops.

By extrapolating the electricity supply curve to liquid fuel production as naphtha from a biomass gasification and Fischer Tropsch synthesis, the equivalent liquid fuel production would be 200,000 barrels (bbl) of oil equivalent per day. We did not calculate the economics of this production, nor did we attempt to generate a liquid fuel supply curve.

Extrapolating the WGA results to the Billion Ton Study technical potential and assuming the same 50% level of economic accessibility suggests carbon savings of 230 MtC for the electricity option and only 61 MtC for the liquid fuels option. Biofuels production based on cellulosic ethanol is covered in a separate paper of this study.

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Tackling Climate Change in the U.S.

Potential Carbon Emissions Reductions from Biofuels by 2030

by **John J. Sheehan**
National Renewable Energy Laboratory

Warren Gretz, NREL

Current ethanol production is primarily from the starch in kernels of field corn, but researchers are developing technology to produce ethanol from the fibrous material (cellulose and hemicellulose) in corn stalks and husks as well as other agricultural and forestry residues.

Biofuels do not avoid carbon emissions, but rather provide a new pathway for recycling carbon through the transportation sector on a time scale that prevents net atmospheric accumulation of CO_2.

Fuels made from biomass (biofuels) offer a unique opportunity to reduce the net burden of CO_2 emissions to the atmosphere by providing a mechanism for photosynthetically recycling carbon from the tailpipes of cars and trucks back to biomass grown each year. Biofuels made from agricultural feedstocks (corn, agricultural residues, and energy crops) could save as much as 58 million metric tons per year of carbon (MtC) emissions by the year 2030. Biofuels have the added benefit of reducing U.S. reliance on foreign oil. In 2030 biofuels could supply 20% of the gasoline that was consumed in the United States in 2004.

The relative contribution of on-road transportation to U.S. greenhouse gas emissions has been growing steadily since 1990 when the U.S. Environmental Protection Agency (EPA) began estimating the U.S. GHG inventory (see Figure 1).

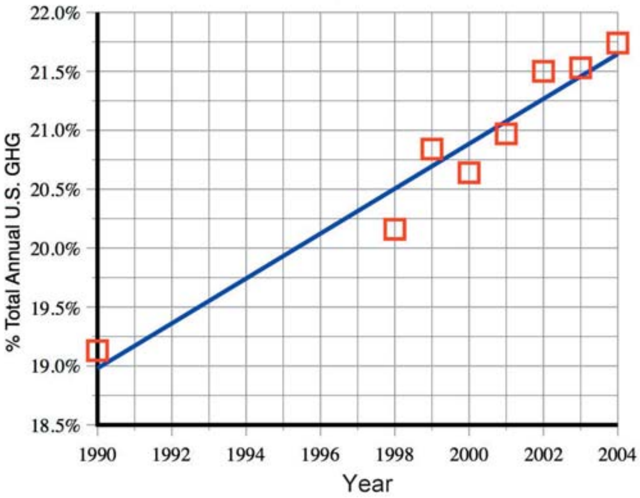


Figure 1. The growing importance of on-road transportation as a source of greenhouse gas emissions in the United States.

The substitution of biofuels for petroleum fuels like gasoline and diesel shifts the flow of carbon into the atmosphere associated with on-road transportation from carbon stored in the ground on a geological time scale to a carbon source that is rapidly (at least annually) recycled between the atmosphere and the biosphere. Biofuels do not avoid carbon emissions, but rather provide a new pathway for recycling carbon through the transportation sector on a time scale that prevents net atmospheric accumulation of CO_2. The efficiency of carbon recycling depends on the source of the biomass and the technologies used in its conversion.

Converting Biomass to Biofuels

A wide variety of technologies are available for converting biomass into transportation fuels. They are often classified in two main categories—thermochemical conversion and biological conversion. Thermochemical routes involve applying heat to break apart biomass into chemical intermediates that can be used to make fuel substitutes. Many of these thermal technologies have been around for well over a century and are used primarily in transforming coal (ancient biomass) into fuels. Biological conversion focuses on fermentation of carbohydrates in biomass to ethanol and other chemicals. Fermentation technology, of course, is among the earliest conversion processes reported in recorded history [6].

The distinction between thermochemical and biological processes is somewhat artificial, in the sense that there are no processes that are strictly biological. Fermentation is typically coupled with some thermochemical processing, either for preprocessing biomass to release sugars in the biomass or for processing of fermentation residues, to make use of the noncarbohydrate fraction of biomass that cannot be readily fermented.

While, historically, the U.S. Department of Energy (DOE) has organized its biomass research and development (R&D) along these distinct technology lines (thermochemical and biological), new analyses described in this paper show that optimal combinations of both biological and thermochemical fuel production may lead to greater energy efficiency in the transformation of the embodied energy of biomass into useable fuels for transportation.

The recently enacted Renewable Fuel Standard established a mandate for renewable fuels that translates into a steady growth in ethanol production up to a level of 7.5 billion gallons per year in 2012.

There is already a thriving biofuels industry in the United States. In 2005, 3.9 billion gallons of fuel ethanol were produced and sold in the United States—primarily from the fermentation of starch in corn grain to ethanol. It is an industry that has witnessed significant growth since its start in the late 1970s, when ethanol blended with gasoline (then known as "gasohol") was promoted as a strategy for reducing our dependence on foreign oil (see Figure 2).

Since 2000, the U.S. ethanol industry has enjoyed growth rates of 10% to 30% per year. The recently enacted Renewable Fuel Standard (RFS) in the Energy Policy Act of 2005 (EPACT 2005) established a mandate for renewable fuels that translates into a steady growth in ethanol production up to a level of 7.5 billion gallons per year in 2012.

Biodiesel is a relative newcomer to the U.S. (and the world) biofuels industry. Recent government incentives for biodiesel have spurred significant growth in the introduction of the vegetable oil-based diesel fuel substitute. Converting vegetable oil to biodiesel is a relatively simple thermochemical process in which the natural oil is chemically combined with methanol to form FAME (fatty acid methyl ester). The fledgling U.S. biodiesel industry tripled its production between 2004 and 2005, reaching 75 million gallons of production.

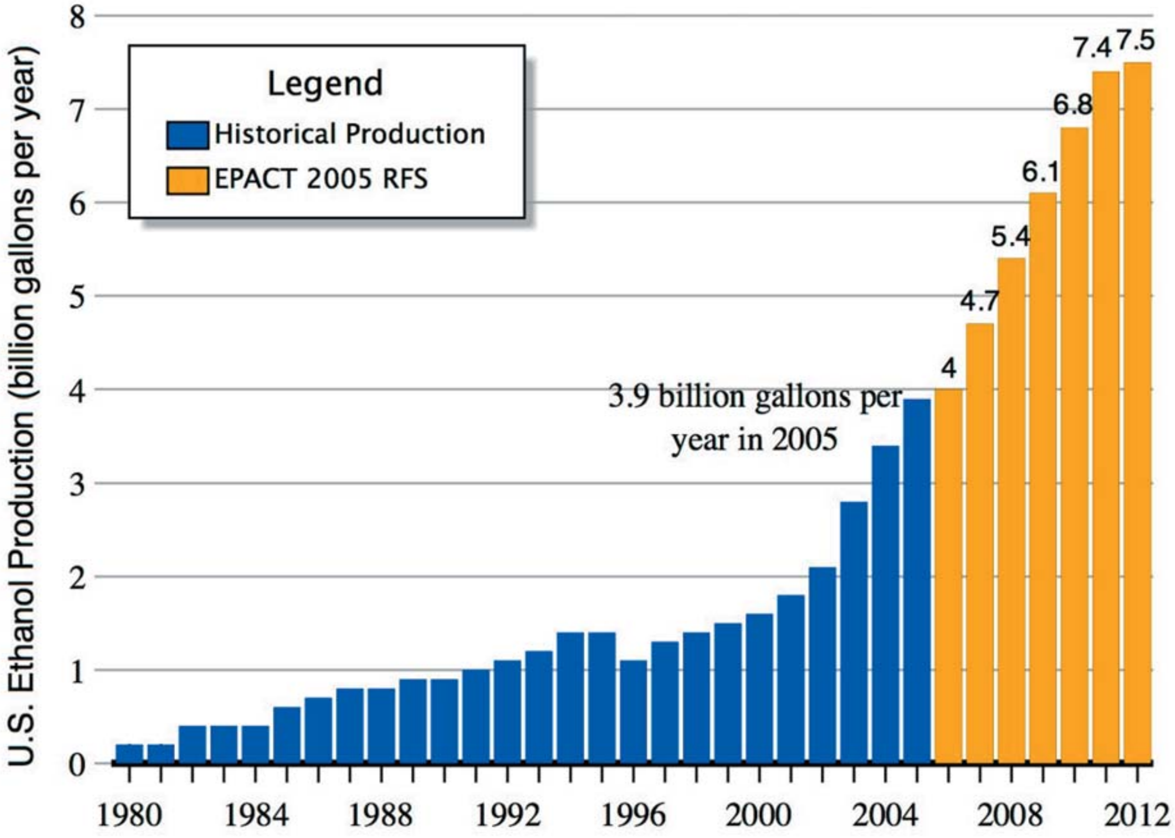


Figure 2. Growth of the current U.S. ethanol industry. (www.ethanolrfa.org)

Tomorrow's Biofuels Industry

Biofuels from conventional crops such as corn and soybeans represent fairly limited resources, compared to the size of the U.S. demand for transportation fuel. One recent study estimated an upper limit on ethanol production from corn at around 10 billion gallons per year [4]. It is likely that the existing corn ethanol and biodiesel industries will be able to meet all of the mandated RFS demand for biofuels. But 10 billion gallons of ethanol production represents a very small fraction of U.S. demand for gasoline, which reached almost 150 billion gallons per year in 2005 [7]. Because a gallon of ethanol contains only 67% as much energy as a gallon of gasoline, 10 billion gallons of ethanol would represent only 7 billion gallons per year of gasoline equivalent—5% of gasoline demand.

For the past 30 years, DOE has sponsored research on the development of thermochemical and biological processes for converting lignocellulosic biomass into fuels. These technologies include:

- **Thermochemical processes:**

  Gasification combined with catalytic conversion of syngas to fuels (e.g., hydrogen, Fischer-Tropsch liquids, mixed alcohols or dimethyl ether [DME])

  Pyrolysis of biomass to produce bio-oils that could serve as intermediates in a petroleum refinery

- **Biological processes:**

  Enzymatic hydrolysis of cellulose, combined with fermentation of sugars from cellulose and hemicellulose and use of the noncarbohydrate residue (primarily lignin) for heat and power production

Accessing lignocellulosic biomass greatly increases the potential supply of biofuels.

The Midwest and West Coast regions of the U.S. offer the greatest concentration of biomass.

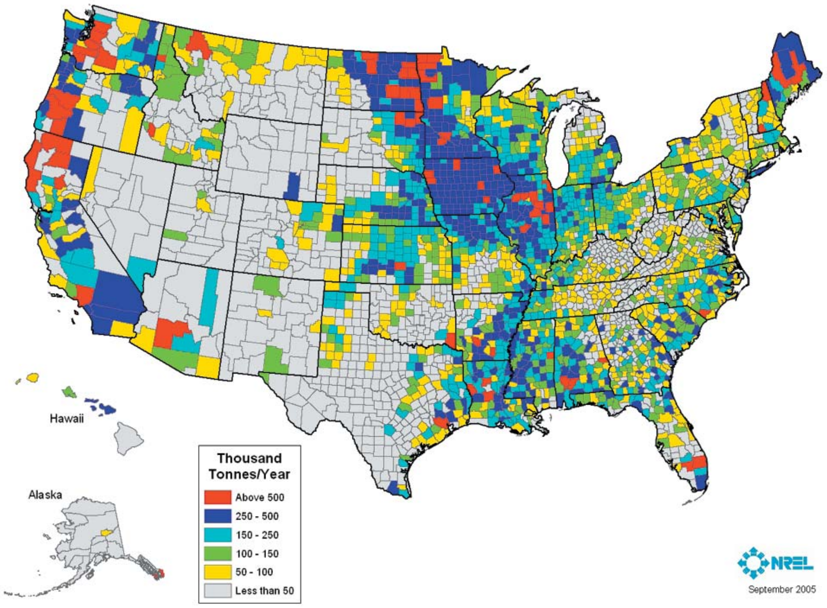


Figure 3. Geographic distribution of lignocellulosic biomass currently available in the United States [2].

See Overend's and Milbrandt's paper for an excellent description of the types, amounts, logistics, and relative distribution of biomass in the United States, as well as a description of some of the logistic issues associated with biomass collection and distribution. Figure 3 shows a recent estimate of the geographic distribution of the various types of lignocellulosic biomass currently available in the United States [3].

This GIS study of current lignocellulosic biomass supply [2] comes up with around 420 million metric tons (Mt) of biomass per year (with 10 Mt associated with methane produced in landfill and municipal waste treatment facilities). The Midwest and West Coast regions of the U.S. offer the greatest concentration of biomass. The Northeast and Southeast regions of the country offer reasonable levels of biomass supply as well.

A 2005 DOE/U.S. Department of Agriculture (USDA) study of biomass potential [4] reported a potential biomass supply of 1.4 billion tons per year (1.2 billion metric tons per year). The goal of the study was to identify scenarios of increased yield, improved farming practices (such as no till) and agricultural land use changes (to accommodate energy crop production) that would lead to a supply of at least 1 billion tons per year. Figure 4 compares the Milbrandt estimate of current available U.S. supply and some of the USDOE/USDA scenarios. Biomass supply is complex and diverse, making such analyses inherently complex and often hard to compare directly. For example, the Milbrandt analysis focuses only on lignocellulosic biomass, while the USDOE/USDA study includes an estimate of the amount of conventional grain crops that could be diverted to biofuels production. However, in general terms, the studies suggest that there is a three-fold range of potential biomass supply, depending on what assumptions are made about future advances and changes in agricultural practices.

While the potential biomass supply estimates shown in Figure 3 and Figure 4 are useful for bracketing the range of the biomass resource, they do not take into account market value and demand for, or cost of, these resources (especially those, such as forest product residues, which already have a use).

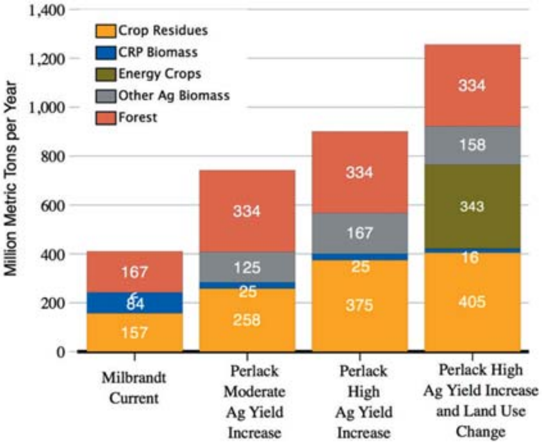


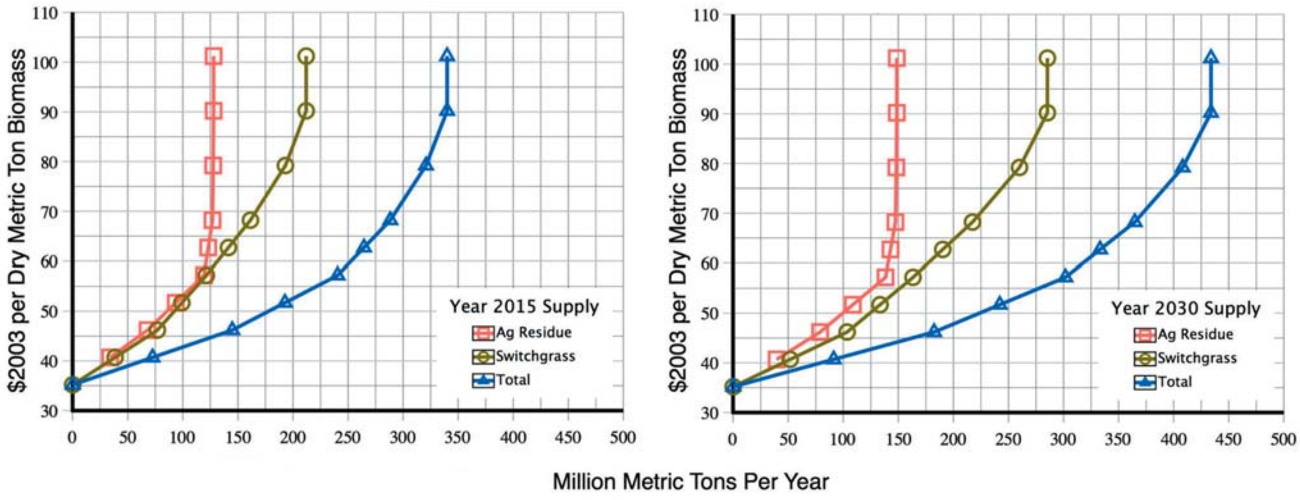
Figure 4. Range of potential biomass supply estimates [2,4].

To avoid some of the ambiguities and complexities of the entire biomass supply, this paper focuses on two of the largest and most straightforward elements of the supply—crop residues and perennial grasses grown for energy production. Neither of these feedstocks is produced or used in large amounts today. Their introduction into the supply will most likely be driven by the demand for energy from biomass.

Supply Curves for Crop Residues and Energy Crops

Figure 5 shows the supply curves for crop residues and energy crops in the years 2015 and 2030 [1]. These supply curves are based on analysis using the University of Tennessee's POLYSYS model—an agro-economic model that allows for competition of prime agricultural land for use in conventional crop production, energy crop (switchgrass) production, and collection of agricultural residues from corn and wheat crops [9,10,11]. The model projects price versus supply data for the period of 2005 to 2014. Extrapolations to 2015 and 2030 are done by assuming no other changes beyond 2014 except a 1% per year increase in corn and wheat yields (and, therefore, in agricultural residue yields) and a 2% increase per year in switchgrass yields. Such sustained increases in yield are well within the historical experience of major crops, such as corn [12].

Total biomass production in 2015 and 2030 tops out respectively at 330 and 420 million dry metric tons per year. The ultimate levels of agricultural residues are consistent with the estimates reported in Milbrandt 2005, but much less aggressive than the potential projections of Perlack et al. 2005* (see Figure 4). Because Milbrandt 2005 does not consider possible land use changes, switchgrass production on prime cropland is not included. Perlack, et al., 2005 allows for land use changes in their most aggressive scenario (Figure 4). The ultimate levels of switchgrass supply in Figure 5 approach 300 million dry metric tons per year, compared to the potential supply of 343 million dry metric tons per year reported in the aggressive scenario from Perlack et al. 2005.



a) Year 2015

b) Year 2030

Figure 5. Biomass supply cost curve.

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* In addition to aggressive assumptions about future crop yield improvements, the Perlack et al. 2005 aggressive scenario assumes widespread adoption of no-till practices that would lead to increased levels of sustainable residue removal.

Note that POLYSYS results used in this paper represent supply as a function of price to the farmer. These prices do not include costs for delivery of feedstock from the farm to the conversion facility. Overend and Milbrandt 2006 present a general methodology for estimating delivery costs as a function of total conversion facility capacity, yield of biomass on the farm, and the percent of participation by farm operations surrounding a conversion facility. This methodology was used to estimate delivery charges for agricultural residues and switchgrass (see Figure 6).

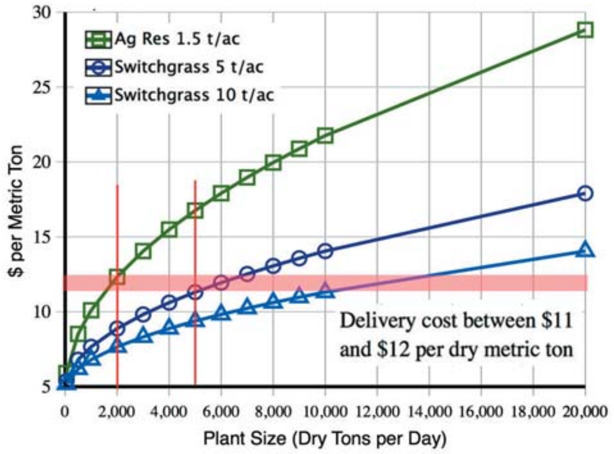

Figure 6. Cost of delivering biomass.

Sustainable yields of agricultural residues (on the order of 1 to 2 tons per acre) are much lower than those of switchgrass, which—on average in the United States —is estimated to be around 5 tons per acre [13,14]. Thus, delivery costs for agricultural residues can be significantly higher than those of switchgrass. Nevertheless, the supply curves shown in Figure 5 include a nominal delivery charge of $12 per dry metric ton of biomass for both resources. This would be consistent with collection of 2,000 dry tons per day of agricultural residues or up to 5,000 tons per day of switchgrass harvested at 5 tons per acre and 10,000 tons per day of switchgrass harvested at 10 tons per acre.

Conversion Costs for Ethanol from Biomass

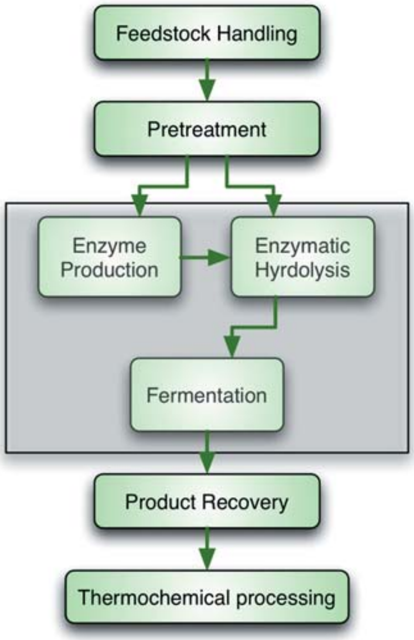

Figure 7. Process schematic of biological conversion of lignocellulosic biomass to ethanol.

To simplify the analysis, only one conversion technology is considered—the biological conversion of lignocellulosic biomass to ethanol (and excess electricity). Figure 7 provides a schematic representation of the conversion process.

The critical technology advancements involve the introduction of biological catalysts that can cost-effectively break down the carbohydrate polymers in biomass to sugars and microbes that can ferment all of the sugars in biomass to ethanol. The technology target for the DOE Biomass Program is to achieve a nominal minimum selling price of ethanol from biomass of $1.07 per gallon of ethanol in the midterm [15,16]. A recently announced presidential initiative for advanced energy technology has proposed a target year of 2012 for this midterm target. Recent analysis of the long-term potential target for ethanol conversion suggests that a nominal minimum selling price of $.62 per gallon of ethanol is achievable by consolidating the enzyme production, hydrolysis, and fermentation capability in one microbe [17,18]. For the purposes of this analysis, the long-term technology target is assumed to be achieved in 2030.

Table 1 summarizes the yield and cost elements of these targets. Commercial availability of the $1.07 per gallon technology is assumed to occur three years after achieving the nominal technology target in 2012. This is because the technology target is assumed to reflect demonstration of technology performance at the pilot scale. Additional scale-up in a commercial demonstration facility, and design and startup of a full commercial-scale operation are assumed to require three years.

The technology targets have other assumptions built in. The targets include a nominal or average price of $35 per dry ton. Such average prices are really a fiction. This price is actually a function of total supply availability (as described in the following section). Perhaps more important is the assumption that the cost of capital is based on a minimum internal rate of return on investment of only 10%. For new technology deployment, this is low. The estimates of inherent processing cost and electricity credit are independent of these assumptions.

Ethanol contains fewer Btus on a volume basis than gasoline. The price of ethanol per gallon of gasoline equivalent can be calculated as

$$[\mathrm{Btu}_{\mathrm{EtOH}}/\mathrm{Btu}_{\mathrm{Gas}}]^{*} \\ [\$/\mathrm{t}_{\mathrm{Deliv\ Biomass}} + \$/\mathrm{t}_{\mathrm{Nonfeedstock\ Cost}}]/\mathrm{Yield}$$

Figure 8 shows the current progress in technology performance improvements along with proposed technology targets expressed as nominal minimum selling price in 2003 dollars per gallon of gasoline equivalent adjusted for energy content. To put these in perspective, the DOE Energy Information Administration's (EIA's) low, reference, and high oil price case projections are provided. The reasons for the aggressive technology target in 2030 relative to projected oil prices are simple. First, it is important to allow for feedstock prices higher than the nominal value of $35 per dry ton as demand for biomass grows. Second, early deployment of the technology will have higher costs of capital due both to allowances by the investor for risk and for inevitable "cost growths" that will occur in first-of-a-kind technology.

Table 1:
Projected conversion cost for ethanol [16,18].

	Year 2015 Yield 99 gal/t of biomass		**Year 2030 Yield 116 gal/t of biomass**	
	$/gal Ethanol	**$/t Biomass**	**$/gal Ethanol**	**$/t Biomass**
Feedstock	$ 0.33	$ 32.96	$ 0.38	$ 43.89
Inherent Processing Cost	0.32	31.77	0.11	13.05
Electricity Credit	(0.09)	(9.18)	(0.12)	(13.86)
Cost of Capital	0.50	49.63	0.25	28.30
Min Price	1.07	105.18	0.62	71.38
Min Price without Feedstock	0.73	72.23	0.24	27.49

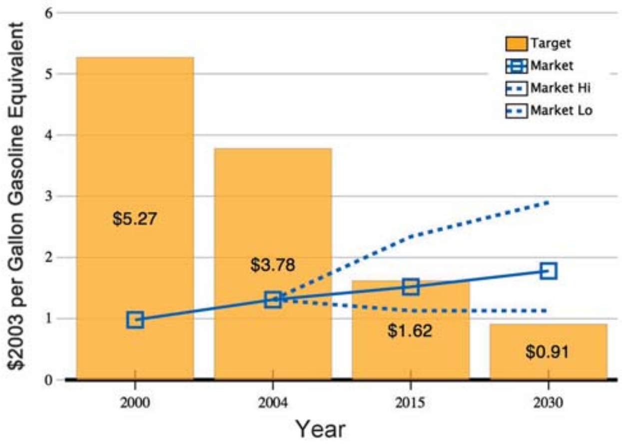

Figure 8. Technology target trajectory for biological conversion of lignocellulosic biomass to ethanol.

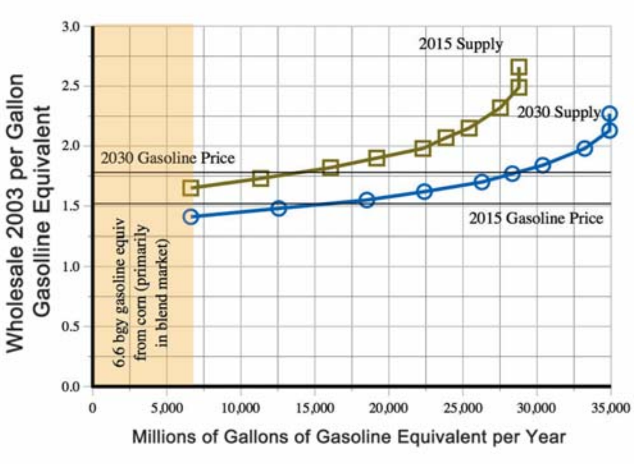

Figure 9. Ethanol supply curves in 2015 and 2030.

Potential Fuel Ethanol Contributions to Gasoline Market

The total gasoline equivalent supply can be calculated as:

$$[\text{Btu}_{\text{EtOH}}/\text{Btu}_{\text{Gas}}]* \text{ Million Metric tons per year*Yield}$$

This relationship can be used to translate biomass supply curves into gasoline-equivalent supply curves for ethanol from biomass, as shown in Figure 9. A total of 28 and 35 billion gallons per year of gasoline equivalent are possible in 2015 and 2030. This includes 6.6 billion gallons of gasoline equivalent from corn grain processing. This assumes that around 10 billion gallons of ethanol made from corn grain will be supplying the needs of the higher value fuel blend market by 2015.

The current RFS already calls for 7.4 billion gallons of ethanol in the fuel supply by 2012. Because of its established commercial position and relatively low risk, corn ethanol technology will likely take all of this market share. Perlack et al. 2005 assumes that up to 10 billion gallons of corn-derived ethanol will be able to penetrate the marketplace. Beyond this level, price pressures on both the supply and the demand side will limit corn ethanol's role.

Carbon Savings Supply Curve

Translating market penetration of fuel ethanol into actual carbon reductions requires understanding the full life cycle impacts of fuel ethanol vis-a-vis gasoline. A number of studies have been conducted to look at this question. For ethanol made from agricultural residues [20] and switchgrass [21], reductions in greenhouse gas emissions are 7,000 and 8,000 grams of CO_2 equivalent per gallon of gasoline equivalent displaced, respectively. Assuming the lower value of 7,000 grams of CO_2 equivalent per gallon of gasoline equivalent applies to both sources of biomass, approximately 1,900 grams of carbon equivalent can be saved per gallon of gasoline displaced by cellulosic ethanol. Wang reports lower carbon savings for corn ethanol, on the order of only 2,000 grams of CO_2 equivalent per gallon of gasoline equivalent [21].

These estimates can be used to translate the gasoline displacement curves in Figure 9 to carbon savings curves (see Figure 10). Ultimate reductions in carbon are 58 and 70 MtC equivalent per year in 2015 and 2030.

Maximum Economic Potential of Ethanol

Figures 9 and 10 also show projections for wholesale (refinery plant gate) gasoline prices in 2015, based on EIA's reference case oil price projections through 2030 [7]. In 2015, cellulosic ethanol's nominal minimum price is not competitive with gasoline prices. Thus, in 2015 corn ethanol provides the only savings in gasoline and carbon emissions. Assuming no lags in deployment of the technology and no risk premiums for cost of capital (that is, assuming that the nominal minimum price shown here reflects actual market pricing by investors), these supply curves suggest potential gasoline and carbon savings in 2015 and 2030 as shown in Table 2.

Table 2:
Maximum economic potential savings in gasoline use and carbon emissions in 2015 and 2030.

	2015	**2030**
Gasoline Displacement (Millions of Gallons of Gasoline Equivalent per Year)	6,600 (all corn ethanol)	28,000
Carbon Savings (Million Metric Tons of Carbon Equivalent per Year)	4	58

Savings of 28 billion gallons in gasoline consumption in 2030 represent 20% of total current U.S. consumption of gasoline. While not a majority of future demand, this level of savings could be sufficient to reduce the current pattern of transportation fuel price volatility, which may well be due to the uncomfortably small margin that exists between supply and demand.

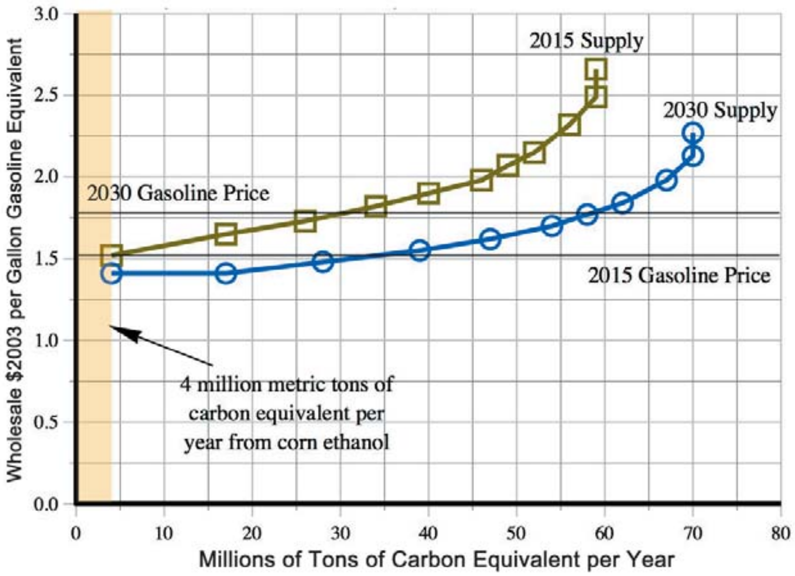

Figure 10. Carbon savings supply curves in 2015 and 2030.

Conclusions

In 2004 a little over 20% of total U.S. greenhouse gas emissions came from transportation. Biofuels serve a unique role in reducing both greenhouse gas emissions and our dependence on oil and gasoline—a critical strategic problem. Savings of 28 billion gallons in gasoline consumption in 2030 represent 20% of total current U.S. consumption of gasoline. While not a majority of future demand, this level of savings could be sufficient to reduce the current pattern of transportation fuel price volatility, which may well be due to the uncomfortably small margin that exists between supply and demand.

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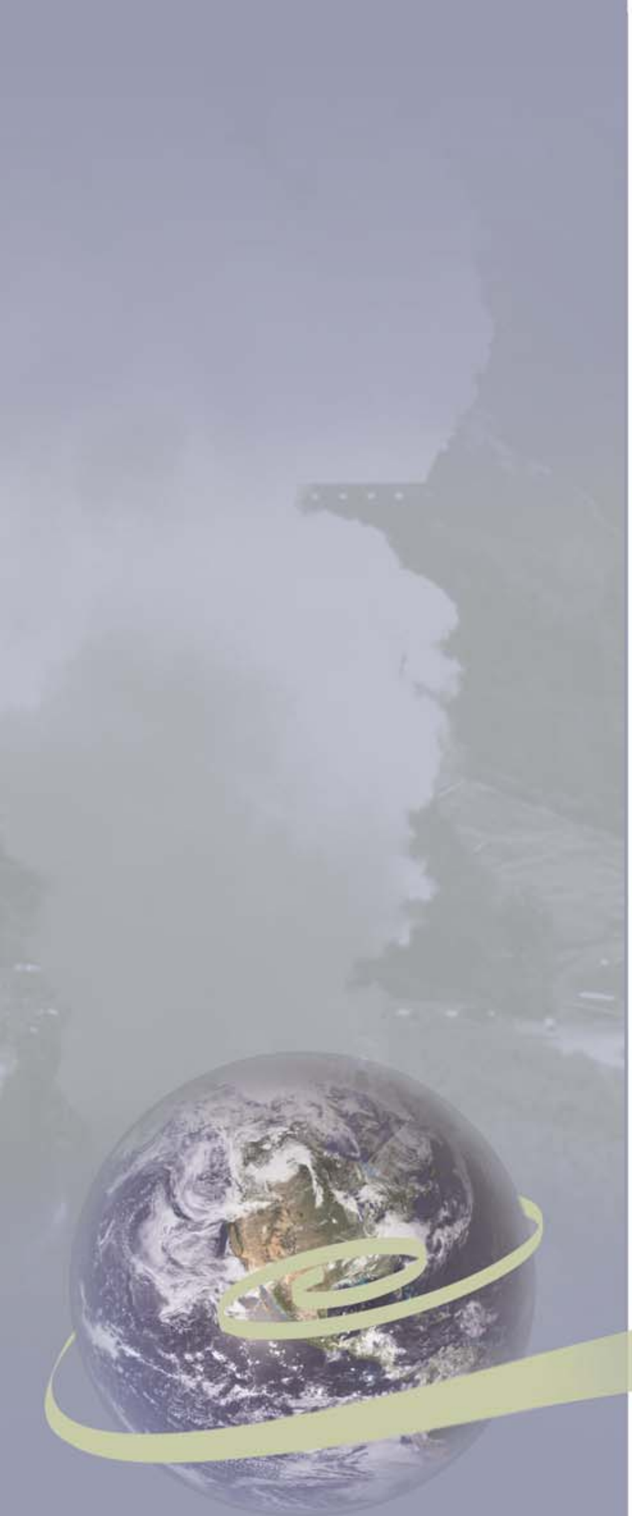
Tackling Climate Change in the U.S.

Potential Carbon Emissions Reductions from Geothermal Power by 2030

by **Martin Vorum, P.E.**
National Renewable Energy Laboratory and
Jefferson Tester, Ph.D.
Massachusetts Institute of Technology



Pacific Gas & Electric, NREL PIX 0060

The Geysers, a dry steam geothermal field in Calistoga, California, is the largest producer of geothermal power in the world.

The scale of stored geothermal energy is so much larger than current demand that even very low geothermal energy recovery could displace a substantial fraction of today's fossil fuel demand.

There is a vast resource of geothermal energy stored as heat in water and rock strata at drillable depths of about 2 to 6 miles (3 to 10 kilometers [km]) within the Earth. Hot water and steam do flow naturally to the surface through fractures, vents, and other high-permeability features, and those resources can be put to use. But these make up a few fortunate cases and are rarely of a high capacity or of the energy intensity needed to economically convert thermal energy to electricity.

There are also geothermal reservoirs throughout the world that have relatively high permeability and contain fluids at shallow depths that are tapped to extract steam or hot water to "mine" geothermal energy for electric power generation. These reservoirs are termed "hydrothermal convective" systems, and some can produce power at costs that compete with conventional energy sources. These, too, are a limited set of resources that offer recoverable heat to satisfy part of the United States' energy demand.

However, an overwhelming proportion of sources of geothermal energy reside in the stored thermal energy contained in rock systems that are uneconomic to tap because of depth, relatively low permeabilities, or lack of water as a carrier fluid for the heat energy. Research sponsored by the U.S. Department of Energy (DOE) seeks to greatly expand the competitive potential of geothermal power generation. A long-term goal is to develop Enhanced Geothermal Systems (EGSs) for energy recovery. EGS technology offers ways to overcome these limitations, but such resources are not yet viable as heat mines to provide energy at competitive prices.

The Geothermal Resource

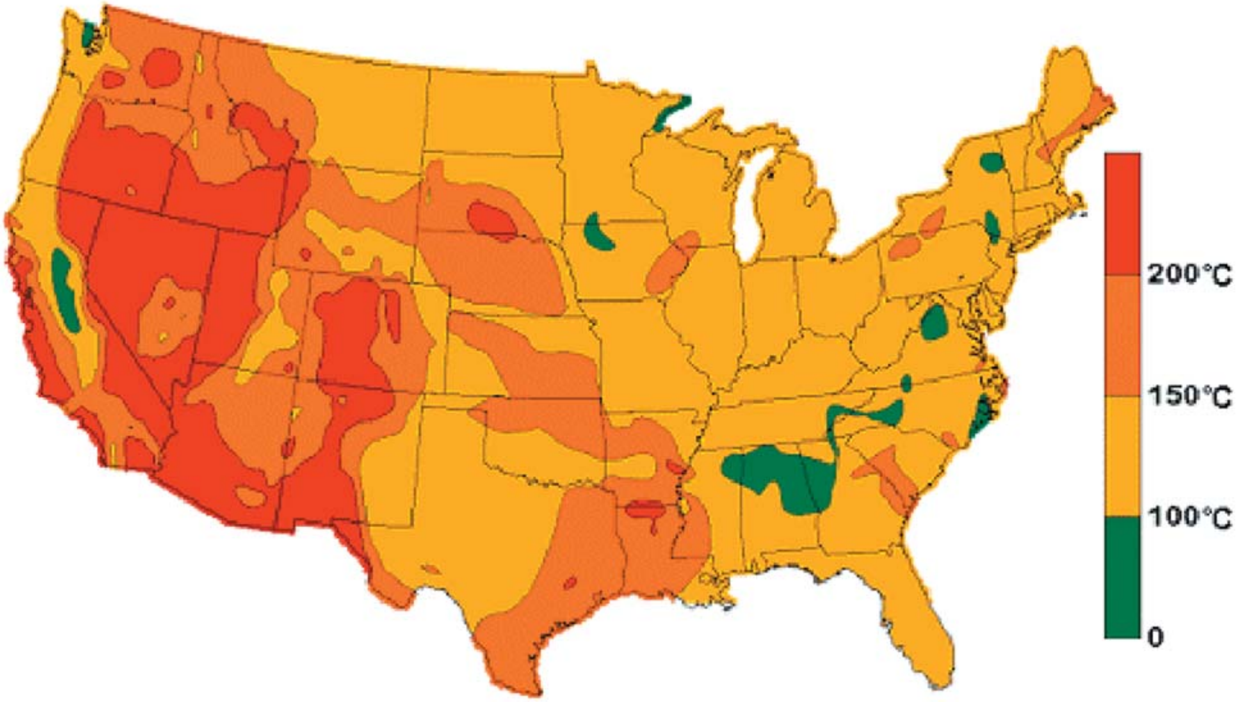


Figure 1: Geothermal temperatures at 6 kilometer depth.

The geothermal resource in the United States is geographically diverse, as measured by distributions of temperatures at various depths. Figure 1 illustrates this in a map of geothermal temperature contours at a depth of 6 km [4]. Table 1 lists estimates of energy distributions as total stored thermal energy, or total heat-in-place [2].

As listed in Table 1, the energy content stored at 3 to 10 km depths in U.S. geothermal resources is vastly greater than the national annual energy demand. For example, the DOE Energy Information Administration (EIA) [5] reports that in 2003, the total U.S. energy demand accounted for about 98 quads, of which 84 quads were from fossil fuel sources, while the geothermal resource storage is about 14 million quads. (1 quad = 1 quadrillion British Thermal Units [Btu] = 1.06 exajoules [$1\text{x}10^{18}$ joules].) This is reassuring, in that the scale of stored geothermal energy is so much larger than current demand that even very low geothermal energy recovery could displace a substantial fraction of today's fossil fuel demand. The sum of stored energy-in-place plus steady-state conduction upward from the Earth’s core could sustain foreseeable geothermal energy withdrawals over very long time periods. And geothermal energy offers deep cuts in the very large rates of emissions of carbon dioxide and other greenhouse gases (GHGs) produced by burning fossil fuels to generate electricity. Ultimately, opting to develop geothermal energy sources would virtually eliminate the GHG emissions for every unit of displaced fossil fuel.

TABLE 1:
Estimates of U.S. geothermal resource base total stored thermal energy content* [2].

Resource type	**Heat in Place at Depth = 3 to 10 kilometers (Expressed as 1,000 quads)**
Hydrothermal (vapor and liquid dominated)	2 - 10
Geopressured (includes hydraulic and methane energy content)	71 - 170
Conduction-dominated EGS (depths of 3 to 10 km, above ambient surface temperature)	
• Sedimentary EGS (or "associated EGS," at margins of hydrothermal fields, showing reduced permeabilities)	> 100
• Basement EGS	13,900
• Supercritical volcanic EGS	74
TOTAL	**~ 14,200**

* Thermal energy of co-produced fluids is not included in these resource estimates [2].

However, the challenge of making productive, economic use of geothermal energy lies in its site-specific recoverability—or lack thereof. By contrast, we are bathed in our renewable wind and solar resources—"access" to those resources is not a problem. The economic challenges of using solar and wind resources lie with their conversion and storage technologies.

Economic challenges for geothermal energy differ substantially. The technologies for converting thermal energy to electricity are long proven, and energy storage is not an issue—in fact, the energy is already in storage awaiting extraction. The challenge for competitive, commercial-scale geothermal energy recovery for power generation lies in the risks related to access and extraction from remote resources within the Earth's crust. Although reaching depths of interest does not pose a technical limitation using conventional drilling methods, there is significant technical and economic uncertainty surrounding site-specific reservoir properties (permeabilities, porosities, in-situ stresses, etc.), and the challenges of stimulating sufficiently large and productive reservoirs and connecting them to a set of injection and production wells. Resolving these challenges will in large part determine the amounts of the vast quantity of Earth's stored thermal energy that can be economically recovered. Given the large potential of geothermal, the proportional payback for research and development (R&D) gains is huge.

To illustrate the magnitude of this opportunity, Figure 2 shows a geographically averaged distribution of potentially recoverable thermal energy stored in EGS resources at particular depth intervals to 10 km [2]. This is a depth-wise integration of heat stored in the Earth, as represented for a single depth slice to 6 km shown in Figure 1. The nonlinear behavior reflects the fact that temperature, a measure of thermal energy content, increases with depth. Considering the geographic dispersal of temperature gradients shown in Figure 1, this demonstrates a broad variability of site-specific depths at which cost-effective resource temperatures will occur. Energy content in reservoirs shallower than 3 km is a small fraction of the 14 million quads estimated to lie between 3 and 10 km.

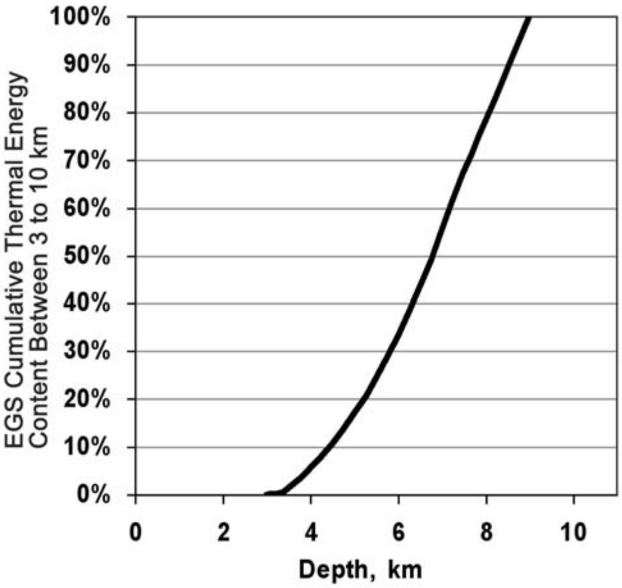


Figure 2: Recoverable EGS energy distribution with depth.

As listed in Table 1, less than 0.1% of the total geothermal energy lies in these typically shallow hydrothermal systems. Although these hydrothermal systems are not discernable on the scale used in Figure 2, they are often characterized by sufficiently high permeability and water content values that allow economic heat recovery in today's energy markets. Nearly 99% of the heat-in-place across the 3 to 10 km horizon resides in reservoirs characterized as sedimentary and basement EGS resources that require stimulation to be productive. Some EGS reservoirs will be relatively more economic than others, depending on local reservoir productivities and capital costs for drilling, stimulation, and energy conversion. By definition, though, they will require some technological advances to be competitive. Additionally, the integrated heat content represented in Figure 2 spans a range of temperatures from which only a part of the available energy would be economically convertible to electricity. This is a function of depth. Thus, drilling to depths greater than 3 km is an inevitable factor in determining site-specific power feasibility.

DOE research into advances needed to foster EGS development assigns goals that fall into four categories, in order of potential impact: reservoir stimulation techniques to produce heat from large volumes of rock, drilling technology to access difficult geothermal zones, energy conversion efficiencies, and exploration. Success of research toward technology development is essential in all four areas to bring large new resources into economic play.

R&D is likely to yield several advantages. First, advances in exploration technology can reduce the risk of positively identifying resources of commercial temperatures and recoverability characteristics. Second, drilling advances will make it possible to access resource temperatures at greater depths and in tougher conditions than are economically competitive today. Third, stimulation is a key technique for enhancing reservoir productivity and lifetime, by increasing connectivity between sets of production and injection wells. This amounts to structurally increasing reservoir permeabilities on a large scale to raise fluid flow rates and heat recovery values. Fourth, conversion advances will use resources more efficiently and at reduced production temperatures, which will both raise thermodynamic efficiency and allow fewer and shallower wells to be used.

Combined gains in all four improvement areas will result in fewer, shallower, or cheaper wells than current technology, reducing capital and operating costs per megawatt (MW) of generation.

Stimulation is conceptually and mechanically simple. First, apply pressure to wells in low-permeability rock formations to induce rock fracturing, then optionally introduce corrosive chemicals and proppants (materials that hold open cracks) to "prop" open new flow paths. A combination of stress and chemical etching may preferentially open flow paths connecting sets of multiple wells. Then, a fluid for carrying heat from the reservoir—water—can be pumped down injection wells and withdrawn from production wells, moving heat to the surface for energy conversion.

Hydraulic stimulation has long been successfully demonstrated in oil and gas production systems. However, it is not yet proven for geothermal systems in long-term applications at commercially high flow rates and heat recoveries.

> *The energy content stored at 3 to 10 km depths in U.S. geothermal resources is vastly greater than the national annual energy demand.*

Potential for Power Production

A group of 17 geothermal technology specialists recently performed a study of the potential of enhanced geothermal systems on behalf of the DOE Geothermal Technologies Program. That work occurred under the auspices of the Massachusetts Institute of Technology (MIT) [2]. A pending report on the work updates data on EGS resources in the United States and provides contemporary estimates of technology performance and economics.

The U.S. geothermal power industry operates power plants predominantly in the West, with a nominal installed capacity of about 2,800 MW [6]. The industry uses hydrothermal resources. Geothermal power systems are best suited to base load operation. They can operate over a modest range of turndown, but as with most technologies that rely on large thermal mass throughput other than internal combustion engines, geothermal plant economics favor steady-state operation at near-full load.

Significantly, the pending DOE report estimates that 2% of the energy in U.S. Enhanced Geothermal Systems (EGS) reservoirs could be recovered as electricity with current stimulation, drilling, and energy conversion technologies. However, the technologies do require advances to cut costs. The study updated estimates of available work and power potential. The in-place energy estimates are integrated from spatial temperature and depth distributions across the U.S. [4]. At the 2% recovery level, the study projects that 2.4 terawatts might be generated over a long-term time frame.

For a mid-term range of four to five decades, the study concludes that a recovery rate of 100 gigawatts (GW) may become feasible. The 2% recovery factor was derived from a starting estimate of 40% thermal energy recovery as a theoretical limit. As a conservative measure, that estimate was reduced to account for practical problems of implementation consistent with field development experience seen not only in the geothermal field, but also in the oil and gas industry. In practice, recovery will be reduced by factors including (but not limited to) flow channeling in a reservoir, failures to maintain initial permeability gains, and long-term changes in flow patterns affecting flow and heat recovery. All such effects would limit heat recovery, though with time and experience they may be overcome. These conservative assumptions are needed to account for cost impacts of uncertainties that are inherent to EGS stimulation technology as an immature discipline.

Temperature differentiates geothermal resources, and energy conversion options play a significant role in power economics as a function of temperature. At temperatures below about 200ºC, binary power systems are favored for relative cost effectiveness. The term “binary” connotes dual-fluid systems, wherein hot geothermal brine is pumped through a heat exchange network to transfer its energy to a working fluid driving a power train. The power train is a closed-loop system that transfers heat from the geothermal brine to the working fluid, then adiabatically evaporates and expands the fluid by mechanical energy recovery (driving a turbine/generator set) and recondenses the fluid by rejecting waste heat outside the system. The working fluid can be from a family of hydrocarbons—a homologous series including butanes through heptanes, for example. Ammonia has also been tested as a working fluid. A key goal of research in binary systems is to increase conversion efficiencies and improve conditions at which the waste heat can be rejected. In general, above about 200ºC, the economics of energy conversion begin to favor flashing geothermal fluids to produce steam, and directly driving turbine/generator sets with the steam.

WGA Estimates of Short-Term Power Production Potential

The Western Governors' Association (WGA) sponsored a recent study [1] that addresses growth scenarios for renewable energy sources. It views renewable energy sources both in competition with and as complementary sources to advanced fossil fuel sources.

A task force of specialists in geothermal power evaluated geothermal power prospects for a 13-state region of the western U.S. over the next 20 years, with a target milestone in 2015. The geothermal task force reported industry-based estimates of prospective power projects in the WGA states. They project that there could be about 5,600 MW of new geothermal capacity within ten years, at wholesale power costs of up to about 8 cents per kilowatt-hour (kWh). Energy costs were estimated as "busbar" values and given as 15-year levelized cost of energy (LCOE) figures.

The WGA task force considered only hydrothermal systems, and it estimated commercialization costs assuming the use of current technologies. The WGA projection assumed that most of the target systems would use binary energy conversion systems.

Table 2 lists the respective state capacities for new hydrothermal power development by 2015. The task force developed a supply curve shown in Figure 3 to illustrate these potentials.

Finally, the geothermal task force considered additional conventional hydrothermal potential that members estimated might also be developed, either in the next 20 years or sooner if market power prices rise. This 20-year potential could bring the total geothermal growth to about 13,000 MW. This is consistent with historic resource estimates for known hydrothermal systems, predominantly in the West.

Table 2:
Projected new hydrothermal power capacities in the western U.S. through 2015 [1].

States	Capacities (Megawatts)	Sites
Alaska	20	3
Arizona	20	2
Colorado	20	9
California	2,400	25
Hawaii	70	3
Idaho	860	6
Nevada	1,500	63
New Mexico	80	6
Oregon	380	11
Utah	230	5
Washington	50	5
TOTAL	**5,630**	**138**

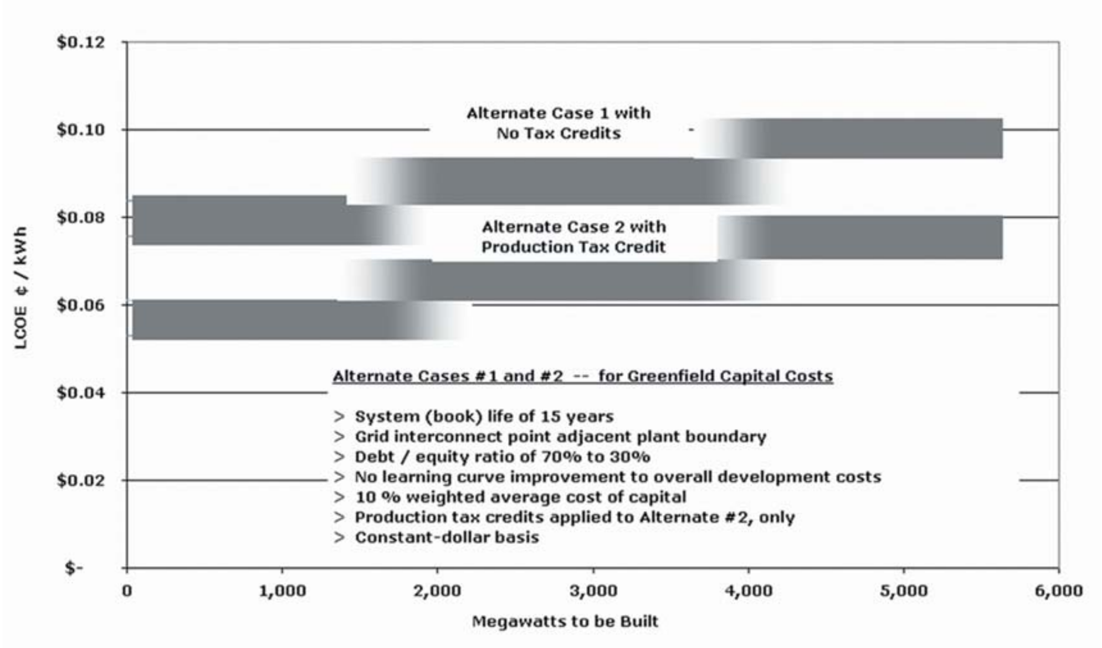


Figure 3: WGA supply curve for geothermal power generation, alternate cases, LCOE versus cumulative generating capacity, 2005 real dollar basis.

Technology Development Economics

Table 3 summarizes DOE estimates [7] of current and future greenfield (i.e., new sites and resources) geothermal power project costs from the Multi-Year Program Plan. The economics of geothermal technologies spans disciplines ranging from geologic exploration to reservoir development, well drilling, and wellfield construction thermal energy conversion. Present-day LCOE estimates range from 8.5 to 29¢/kWh, assuming current binary energy conversion technology is used in hydrothermal and EGS developments. The progressive reductions in LCOE values listed in Table 3 reflect DOE's estimates of impacts of the R&D achievements of the Geothermal Technologies Program.

Table 3:
Estimated generation costs from 2005 MYPP reference cases [6] (2005 U.S. constant dollars).

	Hydrothermal Binary	**EGS Binary**
Reference Case Bases		
Reservoir temperature ºC	150	200
Well Depths, feet	5,000	13,000
LCOE as ¢ per kWh		
LCOE -- as of 2005	8.5	29.0
LCOE -- as of 2010	4.9	
LCOE -- as of 2040		5.5

U.S. geothermal power capacity is dominated by systems using relatively shallow hydrothermal reservoirs and producing steam or flashing brine for energy conversion. DOE research focuses on technology opportunities in exploration, reservoir stimulation, drilling, and energy conversion. Research advances in these areas will empower industry to transition toward a larger pool of resources. The improvements will yield performance gains, improved reliability, and ultimately, reduced unit costs.

The R&D goals aim toward using binary conversion systems at temperatures down to 125 to 150ºC in conjunction with well depths to 4 km (13,000 feet). The goal of the combined temperature and depth values is to expand the resource base for power generation. By comparison, binary systems in use now generally have well depths of a few thousand feet, and they accommodate temperatures marginally below about 200ºC. As shown in Table 3, R&D goals address hydrothermal systems using binary conversion, approaching a DOE Program goal of 5¢/kWh in a near-term of 2010, and in a longer-term time-frame for EGS binary systems around 2040.

The preceding observations describe DOE goals for technical and economic advances by their impacts on what it costs to generate electricity. This is in a context of resource development projects. How, then, do we relate this economic impact of research at the project level to a larger picture, in terms of the U.S. energy economy?

Figure 4 is a current example of a supply curve that has been used to test in-market penetration computations using the National Energy Modeling System (NEMS). NEMS evaluates competing energy resource and technology development impacts in the national energy market. Assessments of resource characteristics and technology economics provide power supply curves as energy cost—LCOE—versus cumulative installed capacity [7]. The upper dashed curve in Figure 4 uses current-technology economics based on 2004 year-end values. The lower curve incorporates DOE research benefits in the form of advances to the technology status.

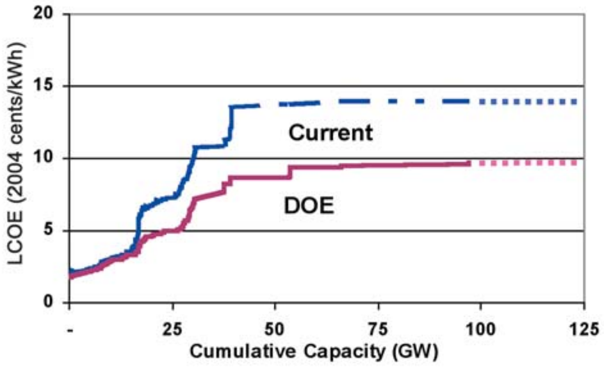


Figure 4. Geothermal supply curves.

These supply curves were constructed as input to NEMS to provide energy costs for a pool of resources up to the 100 GW estimate that the MIT study [2] projected for development by 2050. NEMS estimates forward economic trends 25 years out. The resources total about 100 GW of new capacity distributed in four resource categories:

• Hydrothermal	27 GW
• Sedimentary EGS	25 GW
• Co-produced fluids	44 GW
• Basement EGS	4 GW

This calculation gives a basis for comparison with the NEMS calculations of potential market penetration, discussed below. As indicated by dashed lines at the right boundary of the plots in Figure 4, the resource capacities are estimated to be larger at the price thresholds indicated.

The hydrothermal resource estimate of 27 GW is consistent with a long-standing capacity originally published in the U.S. Geological Survey Circular 790 (1978). The sedimentary EGS category represents resources at the margins of known hydrothermal fields. They are expected to exhibit reduced permeabilities that will require stimulation to achieve economic productivity. Numerous references [2,7] cite oil and gas fields that generate "co-produced" water at temperatures sufficient for power generation with both state-of-the-art and improved conversion technologies. Basement EGS resources are assumed to have very low permeabilities and/or low water content. This category exemplifies resources with high degrees of uncertainty as to their economic viability. It is a small component in this case study but, in terms of both cost and quantity of recoverable energy, basement EGS is where stimulation and drilling research offer their greatest dividends.

Altogether, this input set of resource capacities is a very small fraction of the in-place geothermal potential. The resources are selected from a database, including those by Blackwell [3] and others, of temperature and depth information, and assigned estimates of potential productivities [7]. This provides best-cost prospects for a 100-GW resource pool used as a database for NEMS modeling.

The NEMS results project that success in the DOE research goals could result in a competitive, national geothermal power capacity of around 50 GW by the year 2030. Omitting the benefits of the DOE research program, geothermal power is projected at a level of 30 to 35 GW in that timeframe.

Therefore, one answer to the question of what relationship DOE research goals have to the U.S. energy economy is that NEMS predicts that the economy will have a capacity and cost structure that would support 50 GW of new geothermal power generation by 2030, or half of the 100 GW projected for 2050 by Tester, et al. [2]. Furthermore, by contrasting cases that both discount and give credit for technology contributions by DOE research programs, NEMS shows that the benefits of DOE research gains may add 15 to 20 GW of energy development capacity in the 2030 timeframe.

Infrastructure Performance and Emissions Indicators

A large increase in geothermal power generated in the U.S. energy sector would proportionally displace fossil fuel emissions. Here are data from the EIA that yield the estimates of emissions reduction on the next page [4].

In 2004, total U.S. fossil fuel use for power generation plus combined heat and power (CHP) was stated as fuel consumption and net power output, as follows. The data suggest that the CHP component of the fossil fuel demand is in a range of 5% to 10% of the total. (While the focus here is on geothermal power, a synergy of geothermal heat in CHP applications also offers major potential benefits to overall energy supply.)

• coal	1.0 billion tons per year 2.0 billion MWh (megawatt-hours)
• petroleum	210 million barrels per year 0.1 billion MWh
• natural gas	6.1 million MSCF (thousand standard cubic feet) per year 0.7 billion MWh
• other gases	190,000 MBtu (million British thermal units) per year 0.02 billion MWh
• **total output**	**2.8 billion MWh per year**

As context for the above values in terms of overall U.S. fossil fuel demand in 2004, EIA reports:

- total fossil fuel consumption—86 quads per year
- fossil fuel use for power generation—28 quads per year or 33% of total fossil fuel use
- coal consumption for power generation accounted for generated power as 50% of total watt-hours and 70% of fossil-fueled watt-hours
- coal-fired power plant capacity—335 GW (nameplate) with indicated 67% capacity factor.

Assuming a target capacity factor of 90% for geothermal power plants [1], the coal-fired generating capacity could be replaced by geothermal plants with nominal capacities totaling about 250 GW. This evolution could reduce fossil fuel demand by about 20 quads, accounting for 23% of the 2004 U.S. total fossil fuel consumption.

The Mammoth Lakes Power Plant is located in a picturesque area of northern California. Binary-cycle geothermal power plants release no carbon dioxide or water vapor plumes and blend into the environment.

J.L. Renner, INEEL, NREL PIX 07670

EIA also reports emissions resulting from fossil fuel combustion for electric power and combined heat and power systems for 2004, as follows:

- 2300 Mt of CO_2 (carbon dioxide) (equivalent to 620 MtC), of which 82% was from coal
- 10 Mt of SO_2 (sulfur dioxide)
- 4 Mt of NOx (nitrogen oxides)

The levels of emissions from geothermal power plants are striking when compared to fossil fuel combustion systems. Table 4 lists information from the Geothermal Energy Association [5] that compares the relative rates of emissions discharge per MW of capacity for flashed-steam geothermal power and fossil fuel power plants.

Table 4:
Relative flashed-steam power plant emissions [5] per megawatt of capacity.

	CO_2	NOx	SOx
Fossil fuel	24	4,000	11,000
Geothermal	1	1	1

Flashed-steam systems vent a noncondensable gas stream from their condenser systems. That stream will typically comprise most of the gases naturally occurring in geothermal fluids (except for hydrogen sulfide, which is aggressively scrubbed from the emissions). Carbon dioxide is usually the dominant gas in geothermal fluids, and it is the principal combustion product of fossil fuel power plants. Steam-driven geothermal power systems will typically exhaust about 4% of the CO_2 mass flow of a fossil plant, per equivalent MW of power output.

Significantly, binary systems achieve almost 100% elimination of the gas emissions because the plant systems are closed-loop processes, returning all geothermal fluids—gas and liquid—to the resource.

Figure 5 depicts annual carbon emissions reductions if geothermal power were to progressively displace fossil fuels used for electrical power generation systems, up to the 50 GW capacity that NEMS projects could be competitive by 2030. The upper, solid line represents a CO_2 reduction equivalent to replacing coal-fired power sources. This is reasonable as a replacement fuel basis because both geothermal and coal-fired power plants are optimally designated as base load power generators. The comparison uses capacity factors of 67% per the EIA [5] and 90% per the WGA report [1] for coal and geothermal systems, respectively.

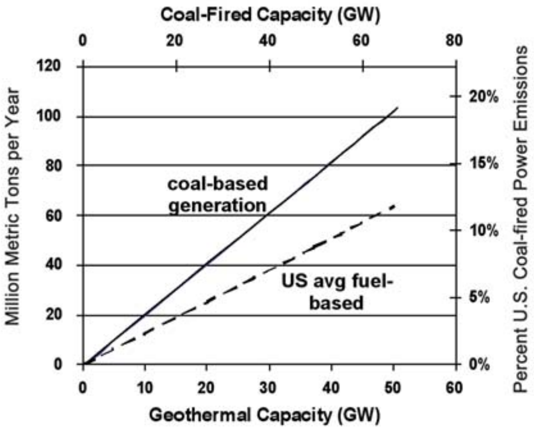


Figure 5. Carbon emissions displaced by geothermal power.

Alternatively, to apply a common fuel basis to compare CO_2 emissions reductions by geothermal sources with other renewable energy technologies, the lower, dashed curve in Figure 5 is based on the U.S. national average fossil fuel heating values and carbon content for power generation. While this fuel equivalence puts the renewable energy sources on a common emissions reference basis, it is more suitable to nonbaseloading energy technologies such as solar and wind power systems. These two technologies are likely to displace a higher proportion of peaking-power sources, driven by lower-carbon fuels such as natural gas, than would geothermal sources.

The projected 50 GW geothermal capacity is roughly equivalent to 70 GW of coal-fired power plants, per the EIA database. This CO_2 reduction assumes using binary conversion systems with near-zero carbon emissions. If the equivalent fossil fuel displacement were achieved by flashed-steam geothermal systems, average carbon reductions would be about 96% of the values in Figure 5. As noted in the preceding section, in 2004 there were 335 GW of coal-fired generating capacity in the United States. If geothermal energy achieves still higher, long-term displacements of coal-fired power capacity, that would further reduce carbon emissions in direct proportion.

Even among those who work in the geothermal industry, these positive technical and economic assessments of energy recovery and power generation potentials leave us faced with a key question—"Why isn't there already more development of geothermal resources for large-scale power generation?" Not unsurprisingly then, people outside the geothermal community tend to undervalue or even ignore its potential.

There are many elements that provide answers to this important question. And they all underscore the need for intensive and long-term research to improve the four key technology areas cited above—exploration, reservoir creation via stimulation, drilling, and energy conversion.

Risk is a most basic, common hurdle to geothermal power growth in the U.S. energy sector. Risk is both a simple, real technical factor in regard to finding a cost-effective resource to develop, and it is a management barrier to commitment of funding at a predictable and competitive return on investment. This simple statement belies the complexity of risk-based limits on funding for resource exploration, engineering development, market (buyer) commitment, and commitment before-the-fact to installing transmission capacity for new power plants to access their prospective markets.

A number of focused technical issues contributes to the real and perceived risks.

Lack of formation water

Geothermal resources are most economical in geologic formations of high permeability that favor flow of water. A worst-case reservoir scenario is absence of water or just very low flow rates. Exploration and development are done to target productive geologies, and to build out from proven productive zones by following trends of permeability and/or enhancing permeability by stimulation. This exemplifies how EGS technology will work in practice. Risk is reduced by starting at productive sites and expanding to bring less productive zones into play. Lack of naturally contained formation water is not a primary barrier. In practice it will be reduced or eliminated by applying EGS stimulation technologies.

Loss of water via cooling

Thermal fluid-driven power systems, such as geothermal technology and most fossil-fueled systems, will work most efficiently using evaporative water cooling. In the arid western U.S. that is a disadvantage because of relatively high rates of evaporation there. For geothermal systems deployed there, it is a dual problem, because cooling water is hard to come by, both economically and environmentally. And failure to return all or most of the groundwater produced for geothermal power will often lead to production decline.

Using dry cooling systems can mitigate evaporative water losses, but they are typically more costly to build and operate than evaporative systems, and they reduce energy conversion efficiency. This is an area of ongoing development, both in industry and DOE research programs.

Elimination of water as a prime mover fluid to recover heat from geologic formations could be an answer to both lack of formation water and cooling system water losses. A potential solution now in early stages of investigation might substitute supercritical carbon dioxide for water as a reservoir heat transfer fluid. Similar to the circulation of water through the reservoir, CO_2 could be compressed and liquefied at the Earth's surface and pumped into a geothermal reservoir for heat recovery. The CO_2 could be returned in a supercritical state to the surface via production wells, where it could drive energy conversion systems. This is a long-term development prospect, with significant practical and economic challenges. If it proves physically possible to sustain this application, it could have ramifications in CO_2 sequestration, providing a significant technological synergy with combustion systems.

Induced seismicity

Injecting and producing geothermal water or steam from hydrothermal and other geologic formations frequently is accompanied by microseismic events. Monitoring and managing seismic activity would be required to ensure stable long-term operation. Predicting and detecting seismic behavior falls under the technology of exploration and reservoir assessment and necessitates gathering and evaluating data from producing geothermal systems.

Drilling and reservoir stimulation

As shown in Figure 2, energy stored in the Earth increases with depth, and permeability is widely variable. The costs of wells make up a major component of the cost of geothermal power. Therefore, the economics of risk can be directly tackled by focusing development R&D on improving the technologies of drilling and stimulating geologic permeability.

Expanded geothermal development clearly carries high potential and a set of challenges. Addressing these challenges is tractable but will require a modest investment to support research and early deployment to reduce risk and uncertainty to acceptable levels.

Expanded geothermal development clearly carries high potential and a set of challenges.

Conclusions

Resource capacities, technologies, and environmental benefits of geothermal energy are expected to advance markedly in coming decades. In a near-term timeframe of about 2015, up to 5.6 GW of new electric generating capacity may be developed using high-grade hydrothermal resources in the western United States, based on current technologies and anticipated busbar costs of up to 8 cents per kilowatt-hour (¢/kWh). Up to 13 GW is projected for development within 20 years, or sooner if market energy prices rise.

Research sponsored by the U.S. Department of Energy (DOE) seeks to greatly expand the competitive potential of geothermal power generation. A long-term goal is to develop EGS for energy recovery. EGS resources may become economically viable, depending largely on the success of engineered enhancements to reservoir productivity and drilling advances. An independent assessment of EGS technology funded by DOE [2] studies the potential for EGS technology to add 100 GW of U.S. generating capacity by 2050 (100,000 megawatts [MW] or 0.1 terawatt [TW]). The study presents a tractable approach to achieve this goal with R&D and deployment support from government and private sectors.

Based on the methodology presented in that study, an ultimate sustainable potential of 2.4 TW is technically possible, using conservative heat recovery factors. In that range of capacities, long-term geothermal energy development could displace a significant fraction of fossil-fueled power generation in the U.S. Therefore, adopting geothermal power on this larger scale could also displace much of the 2.3+ billion metric tons per year of carbon dioxide emitted by conventional fossil fuel-fired power sources in the U.S. today.

Finally, in a third estimate by the National Renewable Energy Laboratory (NREL) using supply curve data by Petty [3] in the NEMS, the U.S. electric sector is projected to call for geothermal power generating capacity of up to 50 GW by 2030.

Including geothermal as an option for base load electricity for the U.S. complements other renewable sources such as wind and solar as well as nuclear alternatives to fossil fuels and can contribute to mitigating climate change.

Acknowledgements

The conclusions presented in this work are the authors' and do not necessarily reflect DOE or NREL policy.

The authors are grateful to the DOE Geothermal Program Management and to NREL for support in presenting this paper. Special thanks go to Chuck Kutscher, Gerald Nix, and Walter Short of NREL, and to Roy Mink and Allan Jelacic of DOE, for their support and interest in this work. The authors gratefully acknowledge contributions of the members of the EGS Assessment Study panel coordinated by MIT [2]. Finally, numerous other individuals generously supported us with final reviews that have been of great benefit in validating the content and making the presentation most accessible to a broad audience.

Resource and economic information cited here reflect historic sources, industry projections, and ongoing studies under the Geothermal Technology Program of the DOE.

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Tackling Climate Change in the U.S.

Potential Carbon Emissions Reductions from Energy Efficiency and Renewable Energy by 2030

Appendix

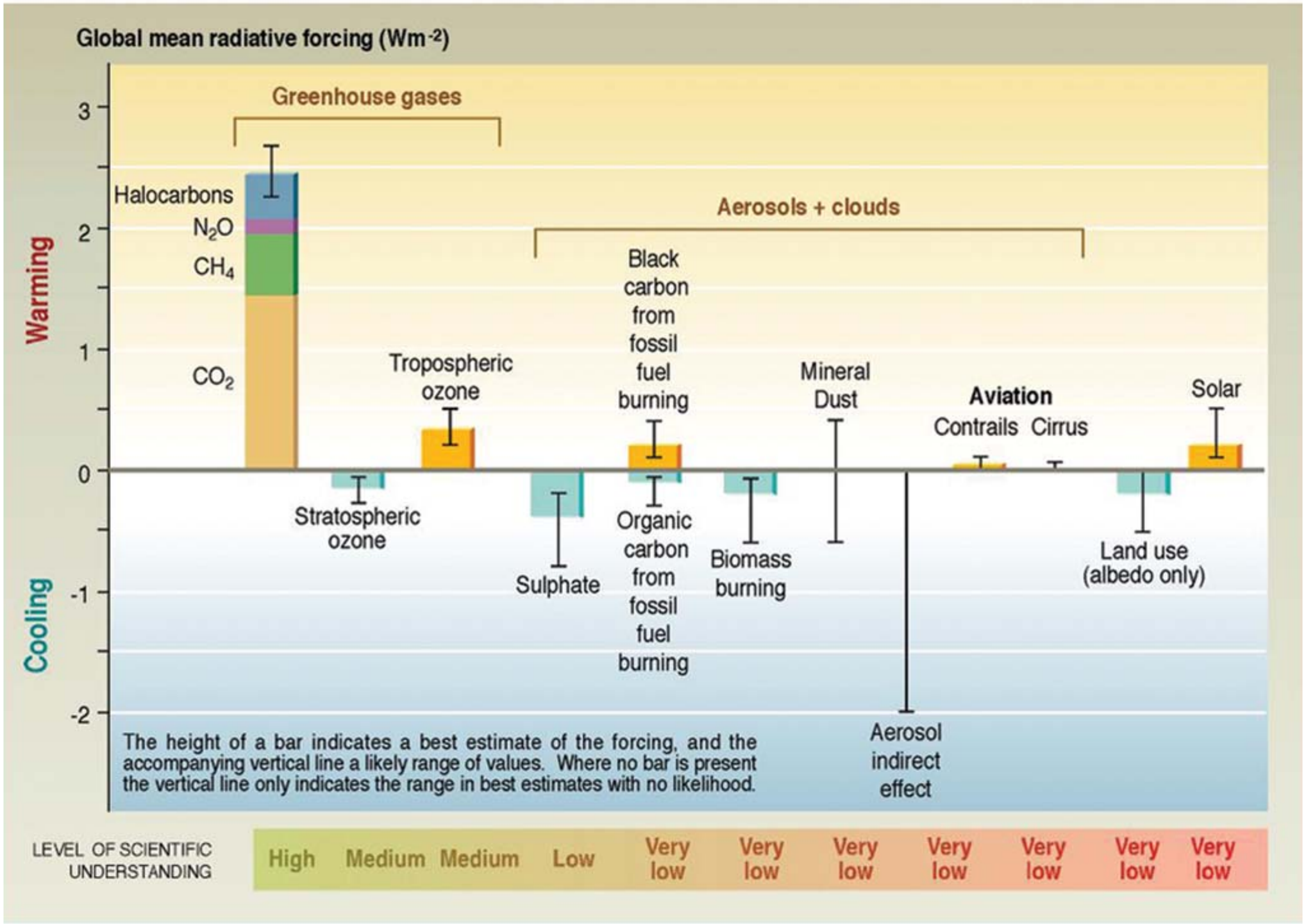

Figure 1. Radiative forcing sources. Carbon dioxide is the largest positive forcing and methane is second. (Source: IPCC Third Assessment Report, 2001.)

An exploding human population burning more and more fossil fuels now has a greater effect on the climate than natural mechanisms.

The Science and Challenge of Global Warming

This appendix was adapted from a feature article by Chuck Kutscher that appeared in the July/August 2006 issue of SOLAR TODAY *magazine.*

Climate scientists who publish in the peer-reviewed literature have agreed for years that humans are changing the Earth's climate. Although most Americans now accept the fact that the planet is warming, polls show that many believe it is simply a natural variation. What exactly is the hard evidence that has scientists so convinced that we are causing the problem, and what can we do about it?

The Science of Global Warming

Since the early 1800s, we have known that various atmospheric gases, acting like the glass in a greenhouse, transmit incoming sunlight but absorb outgoing infrared radiation, thus raising the average air temperature at the Earth's surface. Even though these so-called greenhouse gases are present in very small amounts, without them the average temperature would be about 33°C (60°F) colder than it is today. Some other atmospheric constituents like aerosols released by power plants tend to lower the temperature by blocking sunlight.

Climate scientists compare all the different effects in terms of radiative or climate "forcings" and attempt to calculate how much these phenomena change the net surface heat flux on the Earth (the difference between incoming solar radiation and the outgoing infrared radiation), measured in watts per square meter (W/m^2). Figure 1 shows the radiative forcings as determined by the Intergovernmental Panel on Climate Change (IPCC), an international collaborative of scientists and government representatives established in 1988 to study global warming.

Carbon dioxide, a major byproduct of fossil fuel combustion, is clearly the most influential greenhouse gas. Methane is actually about 20 times as powerful a greenhouse gas as carbon dioxide on an equal volume basis, but it is present in smaller amounts and shorter-lived when added to the atmosphere, so it is less important than carbon dioxide.

The most compelling evidence we have for climate change lies in the so-called paleoclimatic data. In the 1980s scientists began deep drilling to obtain ancient ice core samples in Greenland and Antarctica. Seasonal depositions of snow leave distinct lines in the ice, which, much like tree rings, serve as a timescale. By analyzing air bubbles that were trapped in the ice when it formed, scientists are able to determine the content of greenhouse gases and even the average temperature (which can be inferred from how much heavy oxygen, or ^{18}O, is present) at each point in time.

The data (Figure 2) show that over the past 420,000 years, the CO$_2$ content in the atmosphere has varied cyclically with a period of about 100,000 years (in conjunction with variations in the Earth's orbit) between a minimum value of about 180 parts per million (ppm) by volume and a maximum of about 290 ppm. z(More recent ice cores samples have extended this result back to 650,000 years ago.) And the Earth's temperature has closely followed the greenhouse gas concentration. Other techniques, such as the study of ocean fossils, reinforce the ice core data.

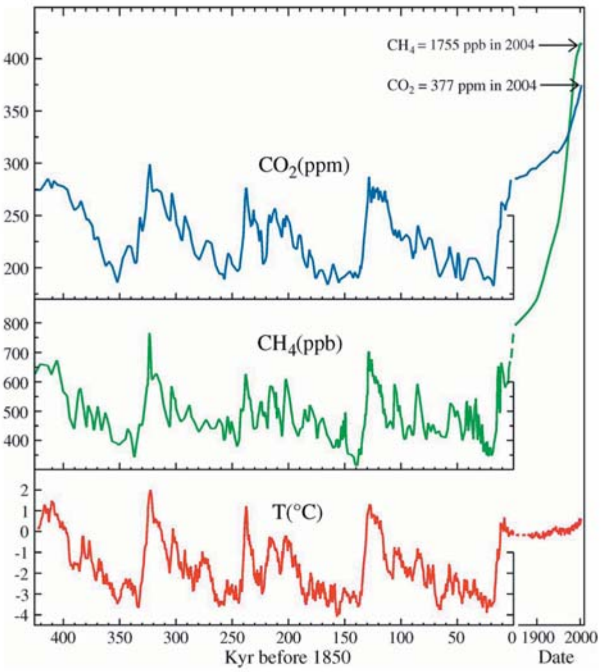

Figure 2. Paleoclimatic data from ice cores. Note the unprecedented recent increases in carbon dioxide and methane. The temperature, though increasing, has not yet reached record levels but will likely do so by mid-century. (Source: Hansen, Clim. Change, 68, 269, 2005.)

Around 1850, when the CO_2 level was still sitting at about 280 ppm, or near the top of a very gradual geological cycle, the level began to shoot upward. It has now reached the unprecedented value of 380 ppm—a 36% increase over the pre-industrial value—and is rising at the incredible rate of about 2 ppm per year. (We owe the American scientist Charles Keeling, who had the foresight to set up a measuring station atop Mauna Loa in Hawaii, for the accurate readings we have of CO_2 levels over the last 50 years.)

In the figure, the timescale from 1850 to the present has been expanded to reveal the shape of the trend, but on the same timescale as the rest of the plot, the rises in greenhouse gases and temperature would appear as an abrupt vertical line. Scientists now know that an increase in temperature can release CO_2 from the ground and seawater, and, conversely, an increase in greenhouse gases will cause a rise in temperature, so the two effects reinforce each other.

Humans' burning of fossil fuels has not just released greenhouse gases, but has also resulted in air pollution in the form of aerosols like sulfur dioxide. To a great extent, these have counterbalanced greenhouse heating by reflecting some sunlight away, and models show that this explains a slight decline in the Earth's temperature between 1940 and about 1970. Air pollution still blocks some sunlight and so reduces global warming. However, with improved air quality standards and rapidly increasing amounts of greenhouse gases, the net effect of humans' burning of fossil fuels is now dominated by the greenhouse effect. In the last 30 years, the average surface temperature of the Earth has been rising at the alarming rate of 0.2°C (0.36°F) per decade.

If one considers all the heat flux human activities have added to the planet since 1850, it would amount to about 1.6 W/m^2 of additional heating over the surface of the planet. The ice core data show us that each watt per square meter of excess net heat flux corresponds to about a 0.75°C (1.35°F) change in the average surface temperature. The 1.6 W/m^2 of additional heating is thus enough to increase the Earth's temperature by 1.2°C (2.2°F).

Since we began burning fossil fuels to produce industrial steam, the surface temperature of the Earth has risen by about 0.7°C (1.3°F). Even if we completely stop adding any more greenhouse gases today, there is still another 0.5°C (0.9°F) temperature rise required to get the Earth back into a state of thermal equilibrium, in which the amount of outgoing infrared radiation is sufficient to match the incoming solar radiation. Of course, in actuality we continue to emit an ever-increasing amount of greenhouse gases, meaning that the radiation imbalance will get worse and the temperature will continue to rise at a rapidly increasing pace.

It is no coincidence that the six warmest years on record have occurred in the last eight years. The year 2005 was the warmest year ever recorded—slightly higher than the previous record year of 1998 (see Figure 3). The high temperature in 2005 is especially significant because, unlike 1998, 2005 had no El Niño to boost the temperature above the trend line.

The Consequences of Global Warming

Since the last ice age, the Earth has been in an extended warm period of about 10,000 years, which is relatively rare in our planet's history. Although paleontologists tell us that modern human beings have walked the Earth for over 100,000 years, it is only during this extended warm period that civilization has blossomed.

It is clear, however, that an exploding human population burning more and more fossil fuels now has a greater effect on the climate than natural mechanisms. We are now the major determinant of the climate of our planet. The atmosphere can no longer be viewed as an infinite sink into which we can dump our wastes.

What are the consequences of not addressing our carbon emissions? The IPCC has identified the potential impacts, and many can already be observed today. They include sea level rises and earlier spring runoffs in many areas, resulting in increased summer drought in some regions. Scientists anticipate worsening drought conditions in Africa, where millions already face famine. Storm severity will increase due to the additional energy in the atmosphere, and a new study indicates that the high intensity of recent hurricanes cannot be explained by a 75-year cycle of hurricane activity.

Low-lying areas like the Florida coast and New Orleans will be more prone to storm surge. This will especially be a hardship on the millions of poor people living in regions like Bangladesh. Mountain glaciers serve as important water sources for many cities around the world. Ninety-eight percent of them are shrinking, and their disappearance will result in severe water shortages for millions of people.

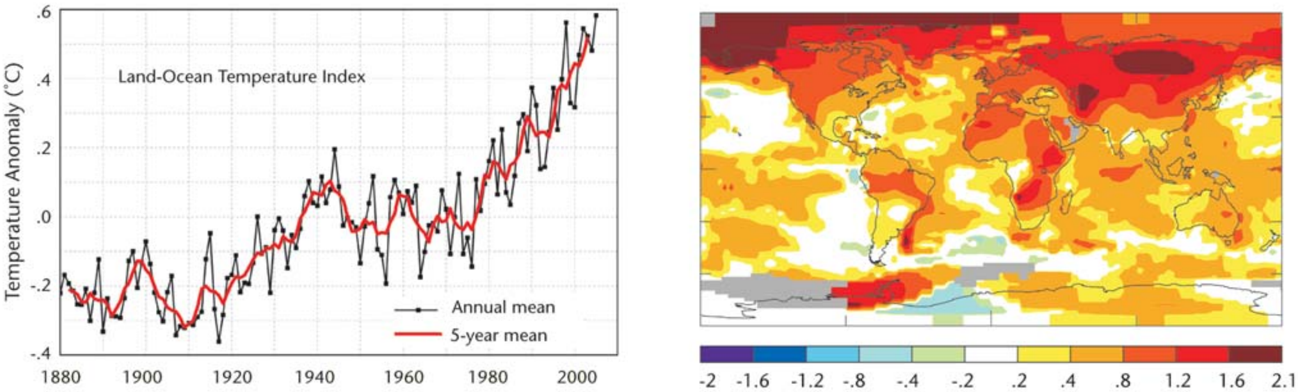

Figure 3. a) Details of global mean surface temperature measurements since 1880. 2005 had the highest global temperature ever recorded. b) The Arctic region has experienced the biggest temperature increases. (Source: Goddard Institute for Space Studies.)

Global warming is also expected to increase the strength of El Niño events that warm the Pacific resulting in more so-called "super El Niños" like those that occurred in 1983 and 1997-98. These extreme El Niños are associated with severe weather-related events around the world including floods (and the diseases that occur in their aftermath), heat waves, mudslides, drought, wildfires, and famine.

Plants, animals, and humans will find it difficult to adapt because the changes are occurring so quickly. It is difficult for animals to migrate to different areas because roads and land development block their paths. The food chain involves a complex interdependence of species, and because different species will react differently to rapidly changing climate conditions, the food chain will be interrupted. As a result, many species will become extinct, and a new study has blamed global warming for the recent extinction of certain frog species.

In many cases, insects and germs will spread beyond their current boundaries, and we are now seeing insect-borne diseases of the tropics, like West Nile Virus, showing up in northern climates. Malaria and crop diseases are likely to also spread. Coral reefs, which provide bountiful sea life critical to the economies of island nations and offer a promising source of new life-saving drugs, can survive only in a narrow temperature range, and are already showing unprecedented die-off due in large part to higher ocean temperatures. Alarming reports from the U.S. Virgin Islands indicate that over a recent four-month period of elevated sea temperatures as much as one-third of the coral has died.

We now know that there are many positive feedback mechanisms in the climate that tend to reinforce changes and can result in a "tipping point" beyond which runaway changes will occur that cannot be reversed. It is because of these mechanisms that the Arctic is the region hardest hit by climate change.

As the ice melts, the resulting darker water and ground absorb more sunlight, thus exacerbating the warming. The average air temperature in Alaska has increased an incredible 2.8°C (5°F) in just the last 50 years. This has caused permafrost to melt, undermining building foundations and even requiring the relocation of entire villages. Polar bears, which venture out onto summer ice after their cubs are strong enough to feed on seals, are becoming malnourished because the ice is melting sooner.

The destruction of ice sheets, in contrast to their formation, is a wet process. Unlike an ice cube melting slowly on a countertop, the destruction of ice sheets is a highly dynamic, non-linear (i.e., with positive feedback) process. The melt water flows like a river, causing rapid heat transfer and erosion (see cover photo of this report). The melt water also seeps down crevasses and lubricates the base of glaciers, causing them to move much faster. Scientists in Greenland have found that these positive feedback mechanisms have combined to cause an alarming acceleration in the melting of the ice sheet. To make matters worse, the newly exposed soil releases the greenhouse gases methane and carbon dioxide as it heats up, promoting still more warming.

Tackling the Problem

In the U.S. the burning of fossil fuels results in the emission of 1.6 billion tons of carbon per year in the form of carbon dioxide. This represents 23% of the world's total CO_2 emissions—a large proportion considering that we have only 5% of the world's population. Electricity production accounts for 42% of our total carbon emissions, and the burning of transportation fuels accounts for 32%. So targeting electricity generation and transportation fuels will address about three-quarters of our CO_2 emissions.

How much do we need to reduce carbon emissions? The key is what additional temperature rise we can tolerate. Studies have shown that if no action is taken, the most probable rise in the average air temperature at the Earth's surface by the end of this century is about 3ºC (5.4ºF), although much larger increases are possible.

Sea level will rise due to both the thermal expansion of the oceans and the melting of land-based ice sheets. Scientific estimates of how quickly sea level will rise vary widely. However, observations of the paleoclimatic record and recent measurements of the rapid melting in Greenland suggest that the computer models used by the IPCC to predict the melting of ice sheets may be too conservative.

NASA climate scientist Jim Hansen has suggested that sea level rise under the "business-as-usual" scenario of emissions (no action to mitigate climate change) could significantly exceed the IPCC upper estimate of about 1 meter by 2100, and this could reshape the world's coastlines and have dire consequences for the large populations concentrated along the coasts.

Hansen has argued that we should aim to keep the additional temperature rise to under 1ºC (1.8ºF) to ensure that the ultimate sea level rise will be less than 1 meter and to minimize the loss of species. He has further argued that if, as we address carbon emissions, we simultaneously reduce methane emissions (which currently represent 9% of our total greenhouse gas emissions) by approximately a factor of two, a target CO_2 level of about 475 ppm could be sufficient to limit the temperature rise to 1ºC (1.8°F).

Stephen Pacala and Robert Socolow of Princeton have described a simplified scenario that would allow the CO_2 to level out at 500 ppm (a little higher than Hansen's target). It involves maintaining the world CO_2 emissions rate at its current value of 7 billion tons of carbon per year (GtC/yr) for 50 years, followed by emissions reductions. (This will require a monumental effort, because if world emissions continue to grow at the current pace, the emissions rate will approximately double by mid-century, and some believe that Chinese growth will drive the rates even higher.) The amount of carbon emissions that would be displaced over the next 50 years can roughly be represented by the difference between the rising business-as-usual level of emissions and the current level, and Pacala and Socolow approximate this by a triangle on a graph of emis-

The U.S. is responsible for 23% of the world's CO_2 emissions, yet has only 5% of the world's population.

sions vs. time (see Figure 4). The triangle has an area of 175 billion metric tons of carbon (GtC). Because that is an immense amount of carbon emissions, Pacala and Socolow divide the triangle into 7 smaller triangles, or “wedges,” each having an area of 25 GtC. They then hypothesize a variety of different mechanisms that can each displace 25 GtC. Example mechanisms include reducing our energy use via conservation and improved efficiency, switching to less carbon-emitting fuels, capturing and sequestering carbon, and switching to various carbon-free energy sources.

What does this plan mean for the United States? World carbon emissions are split about evenly between developed and developing countries. If the developing countries manage to increase their emissions only 60% between now and 2050, we in the industrialized countries will need to reduce our emissions at roughly the same rate to keep world emissions constant. Accounting for a projected business-as-usual 1.2% U.S. annual carbon growth rate, this will require the U.S. to displace 55 GtC, or about two wedges, of carbon emissions over the next 50 years.

This means our carbon emissions in 50 years would be less than one-quarter of what they would have been under business-as-usual. To put this in perspective, this is approximately equivalent to displacing, on average, a typical 500-megawatt (MW) U.S. coal plant every week for the next 50 years. Even with such reductions, our per capita emissions, now at 5 times the world average, would still be twice the world average.

So how can we make such large emissions reductions? Consider first electricity generation. Emissions are mostly associated with coal- and natural gas-burning plants. Coal is the bigger problem because it is more widely used, contains more carbon, and is burned in plants with lower overall efficiencies. The number-one priority for reducing emissions associated with these plants is to increase efficiency, not only at the point of generation, but also at the point of use. Better building envelope design, use of daylighting, improved refrigerators and other appliances, high-performance windows, compact fluorescent lighting, more efficient air conditioners, and higher insulation levels have already made a big impact, and these types of measures hold great promise to further reduce our electricity consumption.

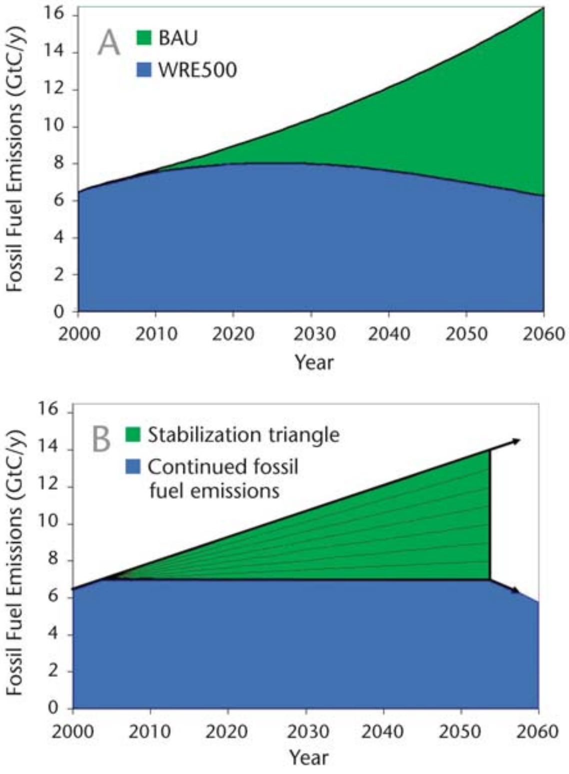

Figure 4. Illustration of A) the business-as-usual and carbon reduction curves and B) the idealized Pacala-Socolow “wedges” approach to describing needed world carbon emissions reductions. Carbon-free energy sources must fill the gap between business-as-usual (BAU) emissions growth and the path needed to stabilize atmospheric carbon at 500 ppm. (Source: S. Pacala and R. Socolow, *Science*, Vol. 305, August 13, 2004.)

But we will still need electricity. To generate electricity and mitigate carbon emissions, there are three main alternatives to coal and gas-burning: 1) capturing the carbon from the fuel and sequestering it in the environment, 2) expanding our use of nuclear power, and 3) switching to renewable sources (wind, solar, biomass, and geothermal).

Capturing and sequestering carbon offers promise. By gasifying coal, for example, it is possible to create a clean-burning fuel and capture the carbon dioxide. This carbon dioxide can then be pumped at very high pressure into geologically stable reservoirs. Carbon dioxide injection is used for enhanced oil recovery, and geologic sequestration has been demonstrated with reasonable success on a small scale.

However, even small leakage rates of CO_2 into the atmosphere could defeat the whole purpose of sequestration (and can be deadly to nearby populations), so sequestration must be demonstrated to work on a large scale, which will be expensive and time-consuming. The availability of feasible geologic storage sites would set an upper limit on how much carbon can be stored. It should be noted that coal burning would still create significant environmental impacts associated with mining and transporting the coal.

Nuclear power is essentially carbon-free. However, the electricity from new nuclear power plants would be relatively expensive, and nuclear faces a number of significant obstacles. The biggest challenges are the disposal of radioactive waste and the threat of nuclear proliferation. New plants would also require long licensing times, and it would likely be at least a decade before nuclear could be brought to bear on the climate change problem.

Of the three alternatives, only the use of renewable energy for electricity generation does not cause additional environmental problems, can be applied to solving the crisis immediately, and is completely sustainable into the future. The major challenges with greatly expanded use of renewables are cost, intermittency of supply, and distance between the resources and the end use.

While centralized concentrating solar power and geothermal electric plants are best suited to the Southwest, there is really no place in the country that doesn’t have access to some form of renewable energy (see map in the Executive Summary of this report). The Great Plains has vast amounts of wind power, the Midwest is rich in biomass, and the eastern U.S. has plentiful biomass and offshore wind. Combine these renewable sources with distributed rooftop photovoltaics, solar hot water heaters, and greater energy efficiency in buildings and industry, and it is possible to de-carbonize the U.S. electric grid.

What about transportation? Burning a gallon of gasoline in a vehicle results in the emission of about 3 kg of carbon. Thus an average car emits about a ton of carbon per year. The quickest way to reduce emissions is to raise the CAFE (Corporate Average Fuel Economy) standards and remove the exemption for SUVs.

Hybrid electric vehicles represent an important advance. Recently there has been a great deal of interest in the development of flexible-fuel, plug-in hybrids. Most trips in an automobile are made within a short distance from home. So if a hybrid electric vehicle has enough battery storage to cover a distance of about 10 to 20 miles, and if it can be plugged into the grid to be recharged (at home, at work, or while shopping), it is possible to greatly reduce the amount of gasoline the vehicle uses, resulting in a gas mileage greater than 100 mpg.

If, in place of the gasoline, we use E85 (an 85%-15% blend of ethanol and gasoline) derived from cellulosic ethanol, even higher effective mileages are possible. If enough plug-in hybrid cars are hooked into the grid, all those batteries represent built-in grid electric storage that can resolve the dispatchability issues associated with renewable energy installations like wind farms.

The Next Step

There is no question that the problem before us is daunting. We will have to adapt to a certain amount of environmental damage that will result from our carbon emissions to date and at the same time aggressively reduce our emissions to avoid the worst consequences. While some have called for the equivalent of the Apollo Space Program or the Manhattan Project, Earth Day coordinator Denis Hayes has argued that the effort needed is more akin to the total overhaul of U.S. manufacturing that occurred following Pearl Harbor. In the last several years, state and city governments have shown a commendable willingness to forge ahead in addressing climate change. Regional carbon cap-and-trade initiatives, a national coalition of mayors, and renewable portfolio standards that now exist in 22 states all will have an impact.

However, only a comprehensive national program by the federal government, with strong commitments from both political parties, can truly address the scope of the problem. History has shown that intelligent regulation works better than volunteer programs. For example, a legislated cap on sulfur dioxide emissions with provision for tradable allowances has harnessed market forces to greatly reduce air pollution and acid rain in the U.S. A similar, federally-regulated carbon cap-and-trade policy could provide a strong stimulus for carbon reduction.

Although some business interests have complained about the potential impact on our economy, many corporations, such as Dupont and IBM, have reduced their carbon emissions and improved their profitability in the process. We should focus on the new economic opportunities that carbon mitigation offers and consider the enormous costs we will incur from environmental damage if we do not begin to address the problem.

In fact, the recently released *Stern Review on the Economics of Climate Change* indicates that the costs to the world community resulting from not addressing climate change will be many times the costs of addressing it. The studies contained in this report show that energy efficiency and the many forms of renewable energy can play key roles in the reduction of U.S. carbon emissions.

Author Biographies

Howard Brown (howard_brown@nrel.gov) is a Science Writer at the National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, Colorado 80401.

Marilyn A. Brown, Ph.D., (brownma@ornl.gov) is a Professor of Energy Policy in the School of Public Policy at the Georgia Institute of Technology, D.M. Smith Building, 685 Cherry Street, Room 312, Atlanta, Georgia 30332. During her previous 22 years at Oak Ridge National Laboratory, Dr. Brown held leadership positions in the Engineering Science and Technology Division and the Energy Efficiency and Renewable Energy Program. Her research has focused on the impacts of policies and programs aimed at accelerating the development and deployment of sustainable energy technologies. Dr. Brown holds a Master's in resource planning from the University of Massachusetts and a Ph.D. in geography from Ohio State University.

Paul Denholm, Ph.D., (paul_denholm@nrel.gov) is a Senior Analyst in the Strategic Energy Analysis Center at the National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, Colorado 80401. His area of focus is the grid integration of intermittent renewables, energy storage, and environmental analysis of electric power generation technologies. Dr. Denholm holds an M.S. in physics and a Ph.D. in environmental studies and energy analysis from the University of Wisconsin.

Patrick J. Hughes, P.E., (hughespj1@ornl.gov) is the Building Technologies Integration Manager at Oak Ridge National Laboratory (ORNL), P.O. Box 2008, Oak Ridge, Tennessee 37831. The focus of his 32-year career, including 17 years at ORNL, has been on the research, development, and deployment of sustainable building technologies. Mr. Hughes holds a B.S. in mechanical engineering from the University of Wisconsin, a Master's degree from the Stanford University Engineering Management Program, and an M.S. in mechanical engineering from the University of Wisconsin Solar Energy Laboratory.

David W. Kearney, Ph.D., (dwk@jkearney.com) is President of Kearney & Associates, P.O. Box 2568, Vashon, Washington 98070. Dr. Kearney consults in the commercial development and project implementation of solar thermal electric systems, focused on parabolic trough solar electric power plants and R&D projects to advance the technology. His activities span both U.S. and European activities in the field. He holds a Ph.D. in mechanical engineering from Stanford University.

Charles F. Kutscher, Ph.D., P.E., (chuck_kutscher@nrel.gov) is a Principal Engineer and Manager of the Thermal Systems Group at the National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, Colorado 80401. His research interests include solar heating, concentrating solar power, and geothermal electricity generation. He was the general chair of the SOLAR 2006 35th Annual National Solar Energy Conference held in Denver from July 8 to 13, and organized the special study that resulted in this report as a key part of that conference. Dr. Kutscher holds a B.S. in physics from the State University of New York, an M.S. in nuclear engineering from the University of Illinois, and a Ph.D. in mechanical engineering from the University of Colorado.

Peter Lilienthal, Ph.D., (Peter_Lilienthal@nrel.gov) is a Senior Economist with the International Programs Office at the National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, Colorado 80401. He has been active in the field of renewable energy and energy efficiency since 1978. His technical expertise is in economic and financial modeling and analysis, focusing primarily on electric utility systems, small power systems, and plug-in hybrid vehicles. Since 1993 he has been the lead analyst for NREL's International and Village Power Program and the developer of NREL's HOMER Micropower Optimization Model. Dr. Lilienthal holds a Ph.D. in engineering-economic systems (now called management science and engineering) from Stanford University.

Robert M. Margolis, Ph.D., (robert_margolis@nrel.gov) is a Senior Energy Analyst in the Washington, D.C. office of the National Renewable Energy Laboratory, 901 D Street SW, Suite 930, Washington, D.C. 20024. His main research interests include energy technology and policy; research, development, and demonstration policy; and energy–economic–environmental modeling. Dr. Margolis holds a B.S. in electrical engineering from the University of Rochester, an M.S. in technology and policy from the Massachusetts Institute of Technology, and a Ph.D. in science, technology, and environmental policy from the Woodrow Wilson School of Public and International Affairs at Princeton University.

Mark S. Mehos (mark_mehos@nrel.gov) is Program Manager of the Concentrating Solar Power (CSP) Program and leads the High Temperature Solar Thermal Team at the National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, Colorado 80401. Mr. Mehos is currently a participating member of New Mexico Governor Bill Richardson's Concentrating Solar Power Task Force as well as the Solar Task Force for the Western Governors' Association Clean and Diversified Energy Initiative. He holds a B.S. in mechanical engineering from the University of Colorado and an M.S. in mechanical engineering from the University of California at Berkeley.

Anelia Milbrandt (anelia_milbrandt@nrel.gov) is a Research Scientist at the National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, Colorado 80401. Ms. Milbrandt specializes in geographic analyses related to renewable energy resources. She holds an M.S. in geography from the University of Sofia, Bulgaria.

Michael Milligan, Ph.D., (Michael_Milligan@nrel.gov) is a consultant to the National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, Colorado 80401. Dr. Milligan has worked on grid integration impacts of wind generation since 1992 and has participated in wind integration and transmission studies in many parts of the U.S. He holds a B.A. from Albion College, and M.A. and Ph.D. degrees from the University of Colorado.

Ralph P. Overend, Ph.D., (rpo2@att.net) recently retired from the National Renewable Energy Laboratory, where he was a Research Fellow. Dr. Overend worked in bioenergy and renewable energy sources since 1973 as a strategic planner, manager, and coordinator of research and development in both Canada and the U.S. He holds an M.S. in chemistry from the University of Salford, Manchester, UK, and a Ph.D. in chemistry from the University of Dundee, Scotland.

John J. Sheehan (john_sheehan@nrel.gov) is a Senior Strategic Analyst at the National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, Colorado 80401. Mr. Sheehan's primary research interests include biomass energy technology, sustainability, and strategic planning and analysis. He holds a B.S. in chemical engineering from the University of Pennsylvania and an M.S. in chemical engineering from Lehigh University.

Therese K. Stovall (stovalltk@ornl.gov) is a Senior Research Engineer in the Building Technology Group at Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831. Ms. Stovall's research into building energy conservation stretches back to the early 1980s. Her projects have recently included an assessment of building retrofit options and laboratory evaluations of a variety of insulation materials. She holds a B.S. in mechanical engineering from Purdue University and an M.S. in mechanical engineering from the University of Tennessee.

Joel N. Swisher, Ph.D., P.E., (jswisher@rmi.org) is Managing Director, Research & Consulting, at the Rocky Mountain Institute (RMI), based in Boulder, Colorado. Dr. Swisher leads RMI's energy consulting practice, serving the electric utility industry, municipal and state institutions, and private corporations. He is involved in municipal energy planning with the utilities and power authorities in San Francisco, Sacramento, and Palo Alto, California, and he consults with several investor-owned utilities. He holds a Ph.D. in energy and environmental engineering from Stanford University.

Jefferson W. Tester, Ph.D., (testerel@mit.edu) is the H.P. Meissner Professor of Chemical Engineering at the Massachusetts Institute of Technology (MIT), 77 Massachusetts Avenue, Room 66-454, Cambridge, Massachusetts 02139. For three decades, Dr. Tester has been involved in chemical engineering process research as it relates to renewable and conventional energy extraction and conversion and environmental control technologies. Dr. Tester holds a B.S. and M.S. in chemical engineering from Cornell University and a Ph.D. in chemical engineering from MIT.

Martin Vorum, P.E., (martin_vorum@nrel.gov) is a Senior Analyst at the National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, Colorado 80401. Mr. Vorum's primary research interests include integration of management, economic, and technologic issues for planning, building, and operating systems and troubleshooting design issues that handicap systems' stability, productivity, and safety. He holds a B.S. in chemical engineering from the University of Houston.

Ken Zweibel (ken.zweibel@primestarsolar.com) is President and Chairman of the Board of PrimeStar Solar, Inc., 1740 Skyway Drive, Suite B, Longmont, Colorado 80504. PrimeStar Solar is a Colorado startup developing low-cost cadmium telluride (CdTe) thin film PV modules. From 1979 until 2006, he worked at the National Renewable Energy Laboratory, where he led the Thin Film PV Partnership. Mr. Zweibel holds a B.S. in physics from the University of Chicago.

Achievable potential. Estimate of the energy savings that could be realistically achieved below a given cost level.

Adiabatic. A thermodynamic process that happens without loss or gain of heat.

Balance of system. The parts of a renewable energy system beyond the energy collection components.

Base load. The minimum load experienced by an electric utility system over a given period of time.

Busbar cost. Cost of electricity before it enters the transmission lines.

Capacity (generator nameplate installed). The maximum rated output of a generator, prime mover, or other electric power production equipment under specific conditions designated by the manufacturer. Installed generator nameplate capacity is commonly expressed in megawatts (MW) and is usually indicated on a nameplate physically attached to the generator.

Capacity factor. The average plant capacity divided by the rated or peak capacity.

Cost of saved energy. Levelized net cost of realizing efficiency improvement divided by the annual savings.

Demand-side management (DSM). Utility investments to improve efficiency or shift the time profile of customer energy use.

Dispatchability. The extent to which electricity can be transmitted to a load when needed.

Economic potential. Estimate of the energy savings that would result from implementing all identified technology measures at or below a given cost of saved energy.

Energy efficiency. The use of technology to provide greater access to energy services with less consumption of energy resources such as fuel and electricity.

Energy services. Benefit derived from energy use, such as mobility, lighting, comfort, sanitation, motive power, etc.

Energy intensity. Ratio of energy use to gross domestic product (GDP) or other economic production index.

Fischer-Tropsch liquids. Fuels free of sulfur and aromatic chemical compounds produced from natural gas, biomass, and coal.

Gigaton. 1 billion metric tons.

Integrated resource planning. Utility planning strategy that blends supply- and demand-side resources to minimize cost.

Levelized cost of energy. The total costs of energy divided by the total kWh generated over a power plant's lifetime.

Net metering. A simplified method of metering the energy consumed and produced at a home or business that has its own renewable energy generator. The excess electricity produced by the generating system spins the electricity meter backwards, effectively banking the electricity until it is needed and providing the customer with full retail value for all the electricity produced.

Nominal costs. Costs adjusted for inflation.

Peak capacity. The maximum output capacity of a power plant.

Peak-shaving. Reduction of the amount of electricity drawn from the utility grid during utility-designated peak time periods.

Primary Energy. Energy embodied in natural resources (e.g,. coal, crude oil, sunlight, uranium) that has not undergone any anthropogenic conversions or transformations (from Intergovernmental Panel on Climate Change [IPCC]).

Quad. A unit of energy equivalent to one quadrillion British Thermal Units (1,000,000,000,000,000 or 10^{15} Btu).

Renewable portfolio standard (RPS). A policy set by federal or state governments that a percentage of the electricity supplied by generators be derived from renewable sources.

Solar fraction. Fraction of heating energy supplied by the sun.

Spinning reserve. A generating unit that is operating and synchronized with the transmission system, but not supplying power to meet load. Such a unit can take on load quickly—if a large generating unit goes off-line unexpectedly, for example.

Acronyms

BAU. Business-as-usual

Bbl. Barrels

CCS. Carbon capture and sequestration

CDEAC. Clean and Diverse Energy Advisory Committee of the WGA

CHP. Combined heat and power

COE. Cost of energy

CRF. Capital Recovery Factor

CSE. Cost of saved energy

c-Si. Crystalline silicon

CSP. Concentrating solar power

DOE. The U.S. Department of Energy

DSM. Demand-side management

EGS. Enhanced geothermal systems

EIA. Energy Information Administration

FAME. Fatty acid methyl esters

FCV. Fuel cell vehicle

FTL. Fischer-Tropsch liquids

FTE. Fuel treatment evaluator

GIS. Geographical information systems

Gt. Billion metric tons (gigatons)

GtC. Billion metric tons (gigatons) of carbon

GW. Gigawatt

GWh. Gigawatt-hour

ha. hectare or 10,000 square meters or 2.471 acres

HVAC. Heating, ventilating, and air-conditioning

ICE. Internal combustion engine

IGCC. Integrated gasification combined cycle

IRP. Integrated resource plan

ITC. Investment tax credit

kg. Kilogram

kha. Thousands of hectares

km. Kilometer

kWh. Kilowatt-hour

LCOE. Levelized cost of energy

M. Meter

MBtu. Million British thermal units

MISO. Midwest Independent System Operators

Mt. Million metric tons

MtC/yr. Million metric tons of carbon per year

MTEP. MISO Transmission Expansion Plan

MW. Megawatt

MWe. Megawatt electrical

NEMS. National Energy Modeling System

NREL. National Renewable Energy Laboratory

NTAC. Northwest Transmission Assessment Committee

PPA. Power purchase agreement

PTC. Production tax credit

RMATS. Rocky Mountain Area Transmission Study

RPS. Renewable portfolio standard

SEGS. Solar electric generating system

SSG-WI. Seams Steering Group of the Western Interconnection

TAG. Triacylglycerides

T&D. Transmission and distribution

t. Metric ton

tC. Metric ton of carbon

TWh. Terawatt-hour or trillion watt-hours

TWp. Peak terawatt

WECC. Western Electricity Coordinating Council

WGA. Western Governors' Association

W/m^2. Watts per square meter

Wp. Peak watt

WTF. Wind Task Force of the CDEAC

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