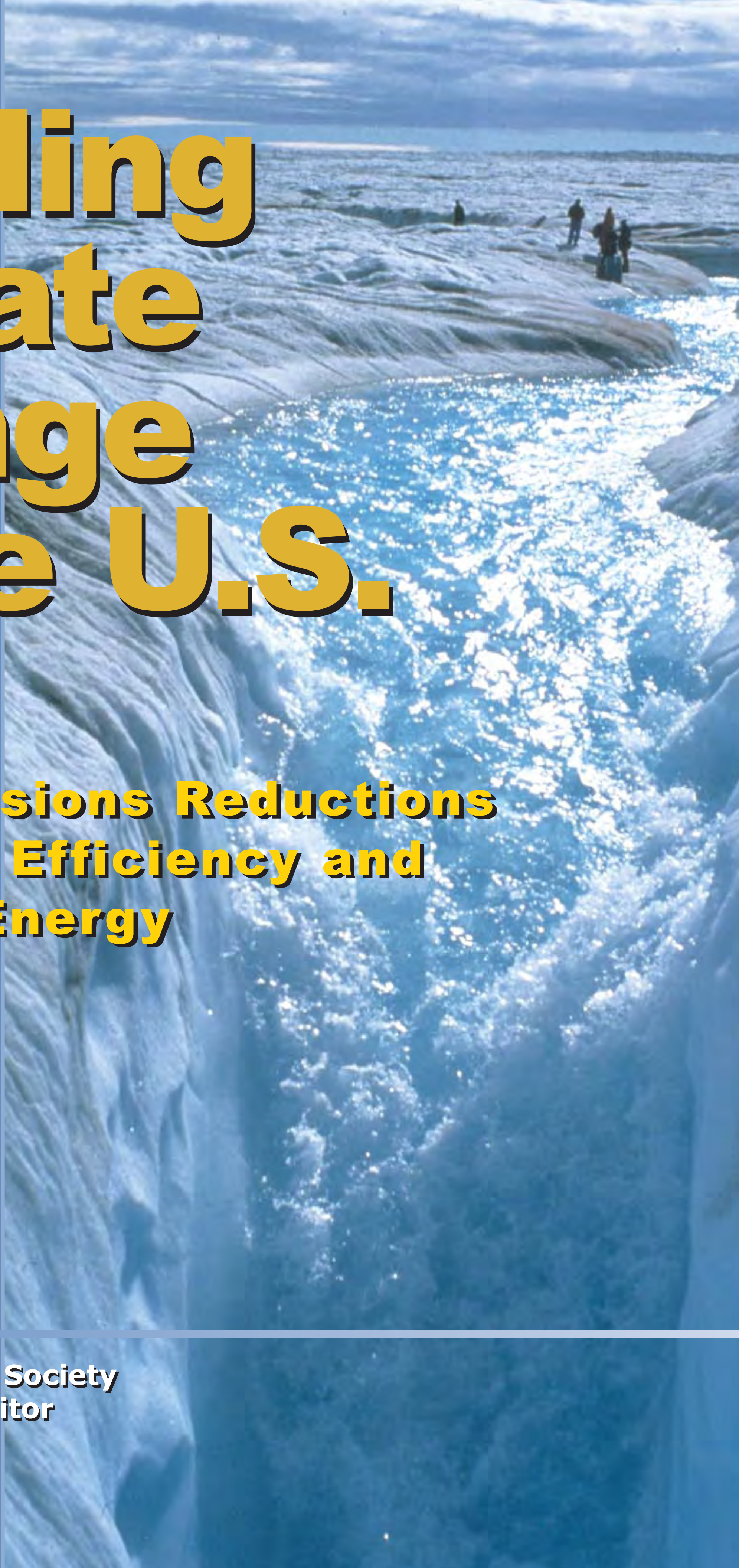


Tackling Climate Change in the U.S.

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.
Photo © Roger Brathwaite/Peter Arnold, Inc

Back Cover: ©Dean Jenkins/morguefile.com.

The publishers of this report gratefully acknowledge Roger Braithwaite's and Peter Arnold Inc.'s generosity and commitment to sustaining our world

Editorial and Design Services, McIntyre Communications Inc.
www.McComm.com

♻ Printed with soy-based ink on recycled paper

Tackling Climate Change in the U.S.

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

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

Table of Contents

ENERGY EFFICIENCY

RENEWABLE ENERGY

APPENDIX

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 likely effects of 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 Jefferson 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.

Brad Collins
ASES Executive Director
January 2007
Boulder, Colorado

LIBRARY OF CONGRESS CATALOGING IN PUBLICATION DATA
Main entry under title: Tackling Climate Change in the U.S.: Potential Carbon Emissions Reductions from Energy Efficiency and Renewable Energy by 2030
ISBN 0-89553-306-5

List of Figures

Executive Summary

Overview and Summary of the Studies

ENERGY EFFICIENCY

Overall Energy Efficiency

Buildings

Plug-In Hybrid Electric Vehicles

RENEWABLE ENERGY

Concentrating Solar Power

Photovoltaics

Wind

Biomass

Biofuels

Geothermal Energy

APPENDIX
The Science and Challenge of Global Warming

List of Tables

Executive Summary

Overview and Summary of the Studies

ENERGY EFFICIENCY

Buildings

Plug-In Hybrid Electric Vehicles

RENEWABLE ENERGY

Concentrating Solar Power

Wind

Biomass

Biofuels

Geothermal

Tackling Climate Change in the U.S.

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

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 – 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 450–500 parts per million (ppm).

What does this mean for the United States? Estimates are that industrialized nations must reduce emissions about 60–80 percent 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 offsetting between 1,100 and 1,300 million metric tons of carbon per year (MtC/yr).

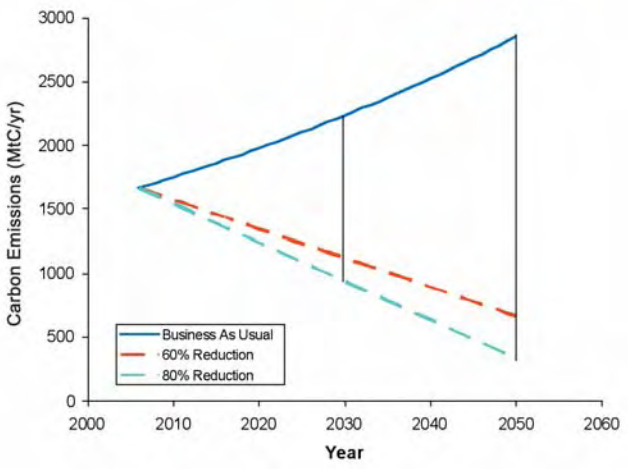


Figure 1. Triangle of U.S. fossil fuel carbon reductions needed by 2030 for a 60% to 80% reduction from today's levels by 2050.

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-offset 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 percent of the total carbon-reduction contribution is from energy efficiency (EE) and about 43 percent 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.

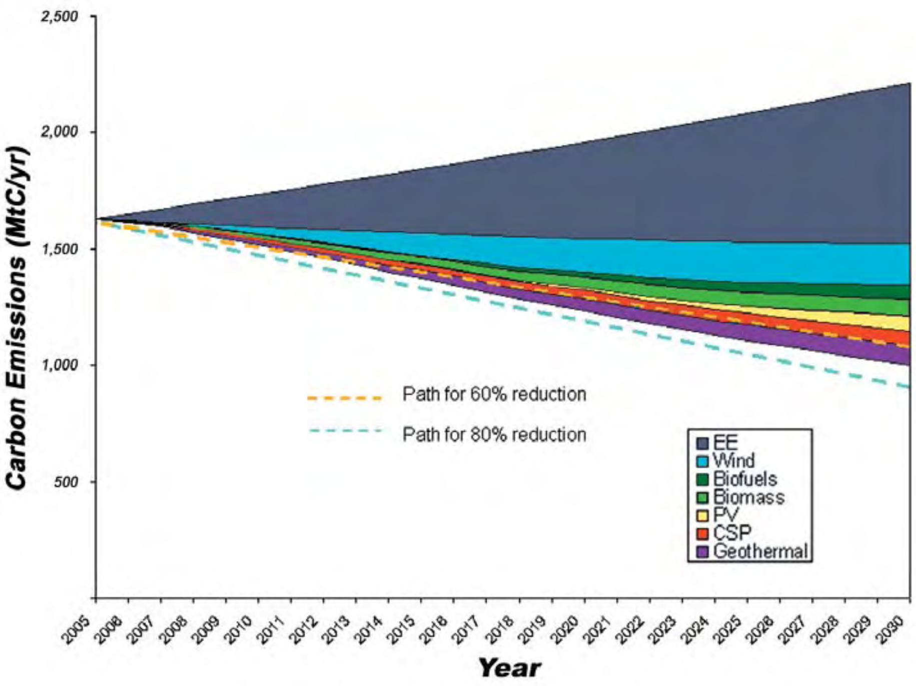


Figure 2. Carbon offset contributions in 2030 from energy efficiency and renewable technologies and paths to achieve reductions of 60% and 80% below today's emissions value by 2050.

Table 1.
Carbon offset contributions (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-offset contributions 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 fully realize these potentials. Integration of these technologies in the marketplace could reduce these numbers 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 percent of the U.S. electric 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 percent 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 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 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.

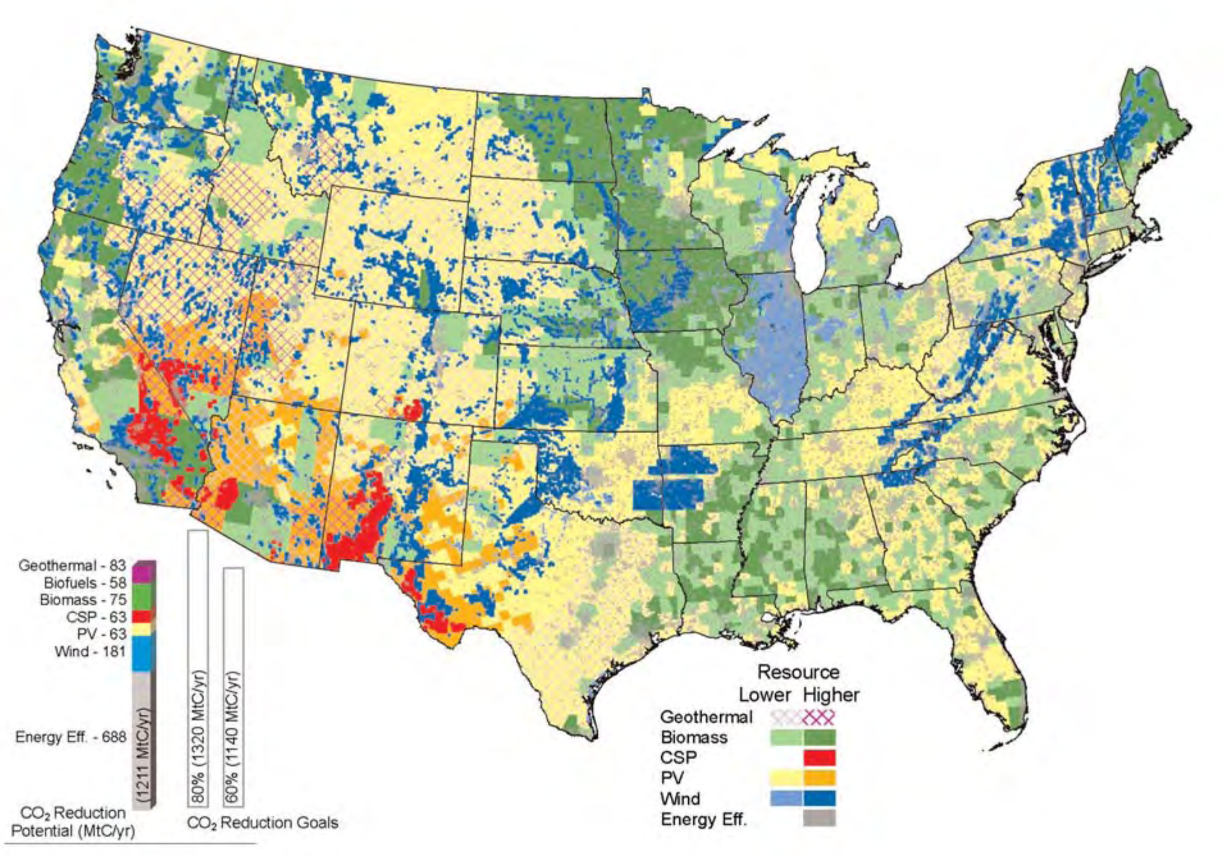


Figure 3. U.S. map indicating the potential contributions from energy efficiency and renewable energy by 2030.

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 cover: NASA
Smaller photos clockwise from left: Sanjay Pindiyath/morguefile.com; Cielo Wind Power/NREL; Charles Kutscher; 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 1 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 offsets 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-offset estimates 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 CO2 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.)

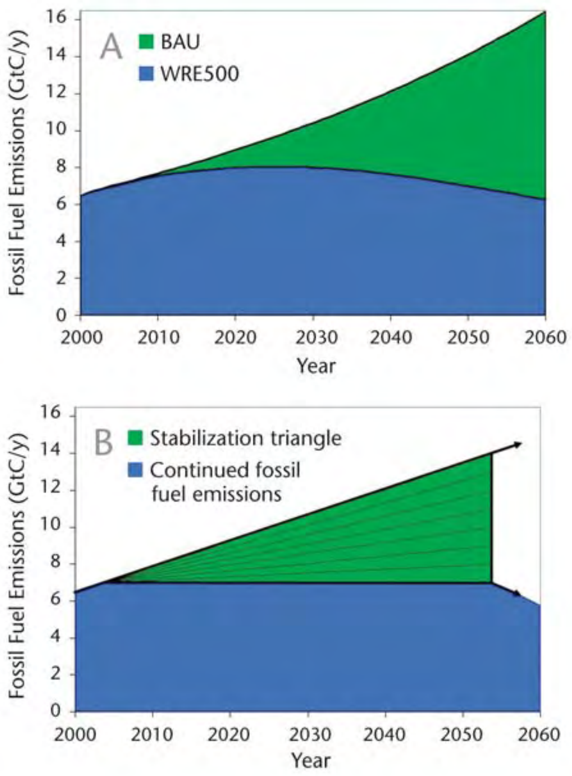


Figure 1. Illustration of A) the business-as-usual and carbon reduction curves and B) the idealized Pacala-Socolow "wedges" approach to describing needed world carbon emissions reductions. Carbon-free energy sources must fill the gap between business-as-usual (BAU) emissions growth and the path needed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

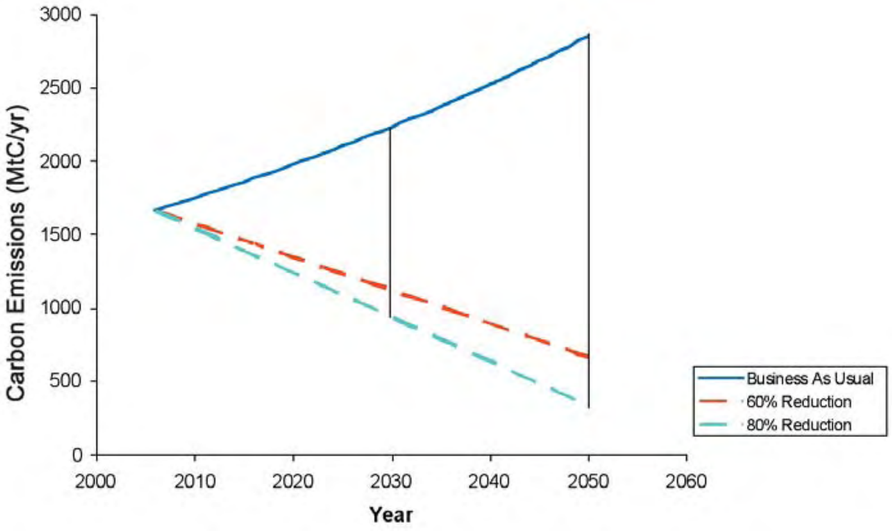


Figure 2. U.S. carbon reductions needed by 2030 for a 60% to 80% reduction from today's levels by 2050.

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 offsetting 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)

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

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

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

Photovoltaics
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 3-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 offset. 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-offsetting 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 24% reduction in electrical energy in 2030. At the lower (national average) conversion of 160 metric tons of carbon per GWh, this provides a carbon savings of 165 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 635 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.

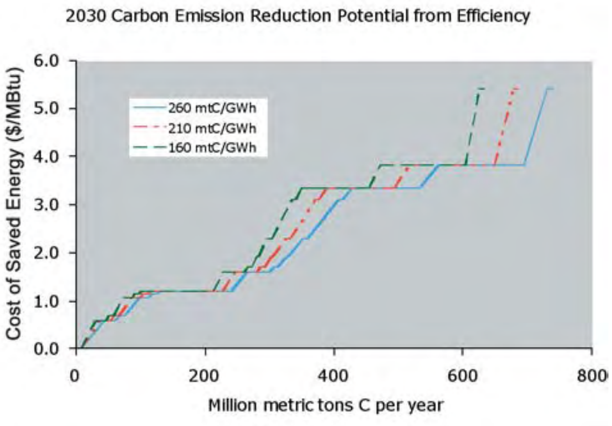


Figure 3. Cost of saved energy (in $/million Btu) versus carbon displacement (in millions of metric tons per year).

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.

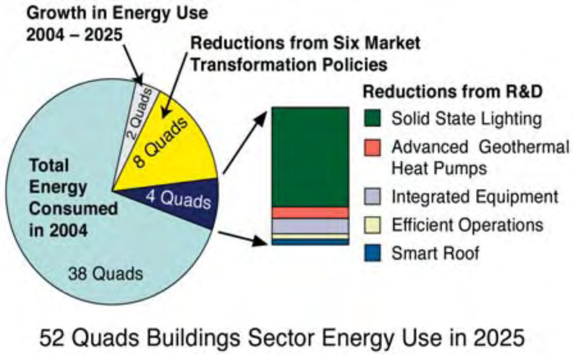


Figure 4. Energy reductions for the buildings sector.

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.

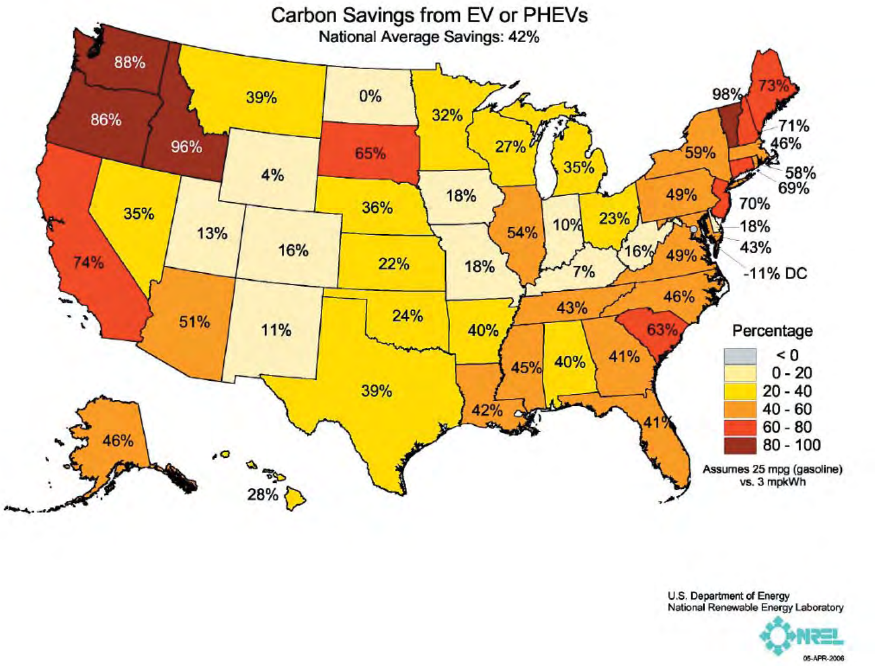
The author of the energy efficiency paper estimates that approximately 40% of the total carbon savings are from buildings. Using the mid-range carbon value, this would correspond to a carbon savings from building energy efficiency of 275 MtC/yr in 2030, compared to a value of 205 MtC/yr in 2025 in the 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.



U.S. Department of Energy
National Renewable Energy Laboratory
NREL
05-APR-2006

Figure 5. Carbon savings for operating a vehicle on electricity versus gasoline by state.

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 and 8 cents per kWh for electricity.

Although the impact of plug-in hybrids is not included in our overall summary of carbon savings, plug-ins help to enable the wind power generation assumed in 2030. 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.

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.

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.

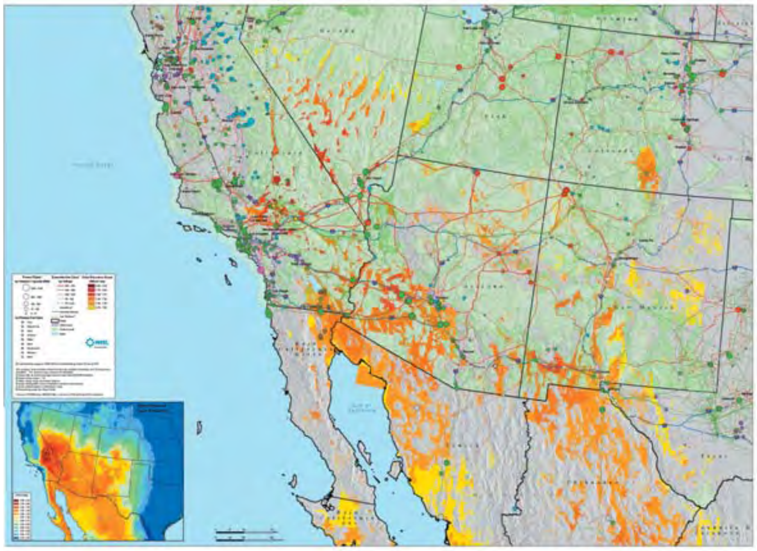


Figure 6. Direct normal solar radiation for U.S. Southwest filtered by resource, land use, and ground slope.

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.

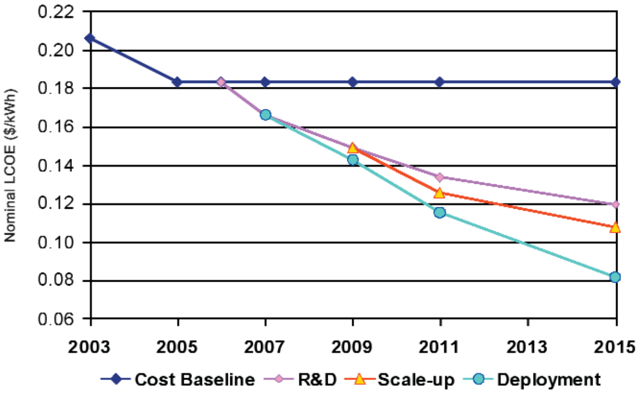


Figure 7. CSP cost reduction curves.

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

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%

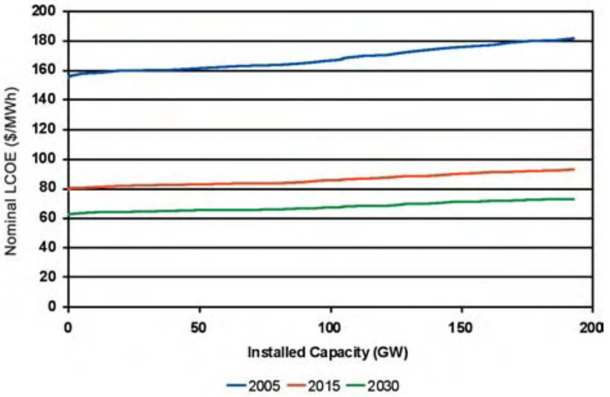


Figure 8. Capacity supply curves for CSP.

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, Concentrating Solar Deployment System Model (CSDS) and Wind Deployment System (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 offset 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, many are still 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.

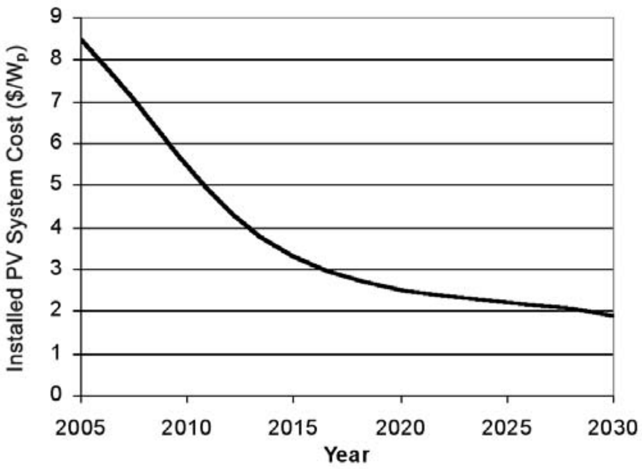


Figure 11. PV cost reduction goals.

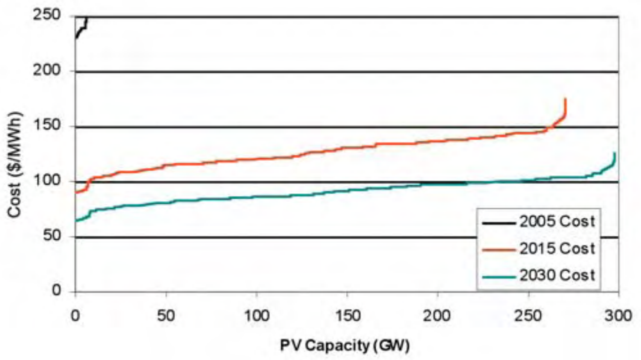


Figure 12. PV capacity supply curves.

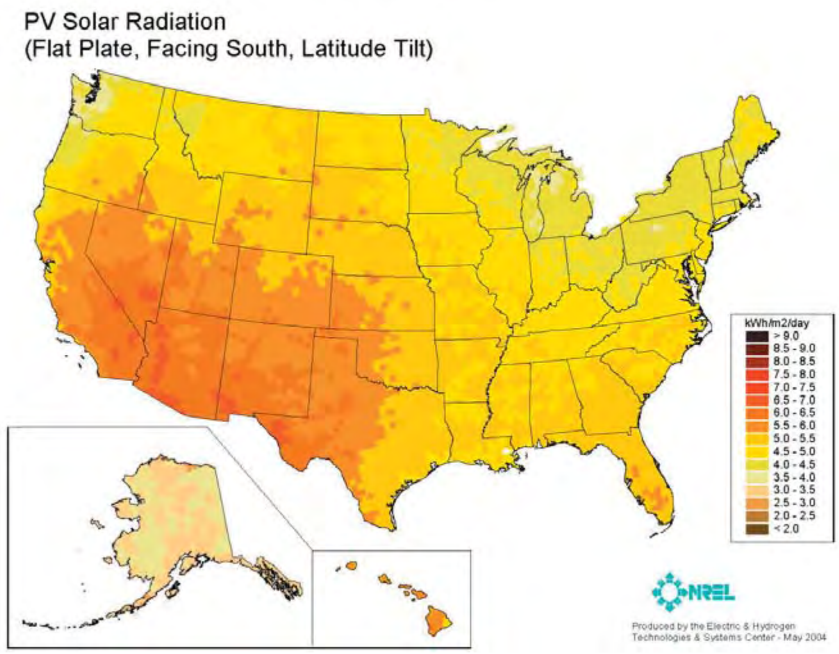


Figure 10. U.S. map of the solar resource for PV.

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 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 we will use this more conservative value. With any of the renewable supply technologies, it is difficult to estimate deployment rates because it 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 2050. 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 offset 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 200 GW 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.

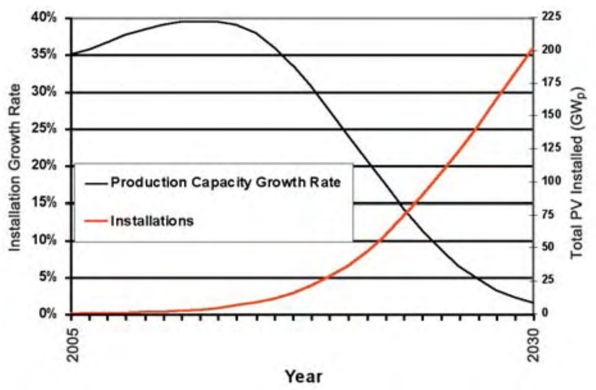


Figure 13. PV production and field deployment scenario to 2030.

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 in the United States. It is concentrated throughout 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 – 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.

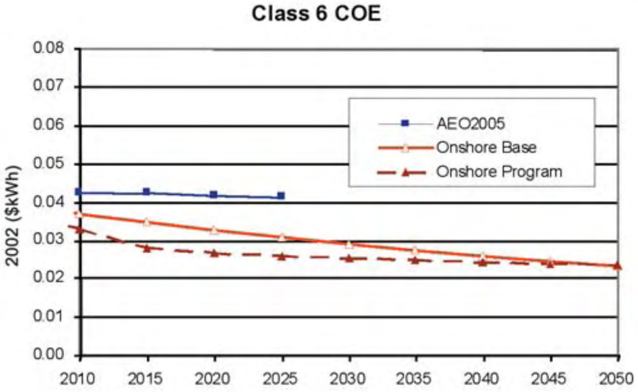


Figure 15. Expected reductions in the cost of wind power. The lower red curve (Onshore Program) denotes the low-wind speed turbine (LWST)/Wind Program goal to reduce costs. The Onshore Base red curve is the "base case" without the LWST.

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

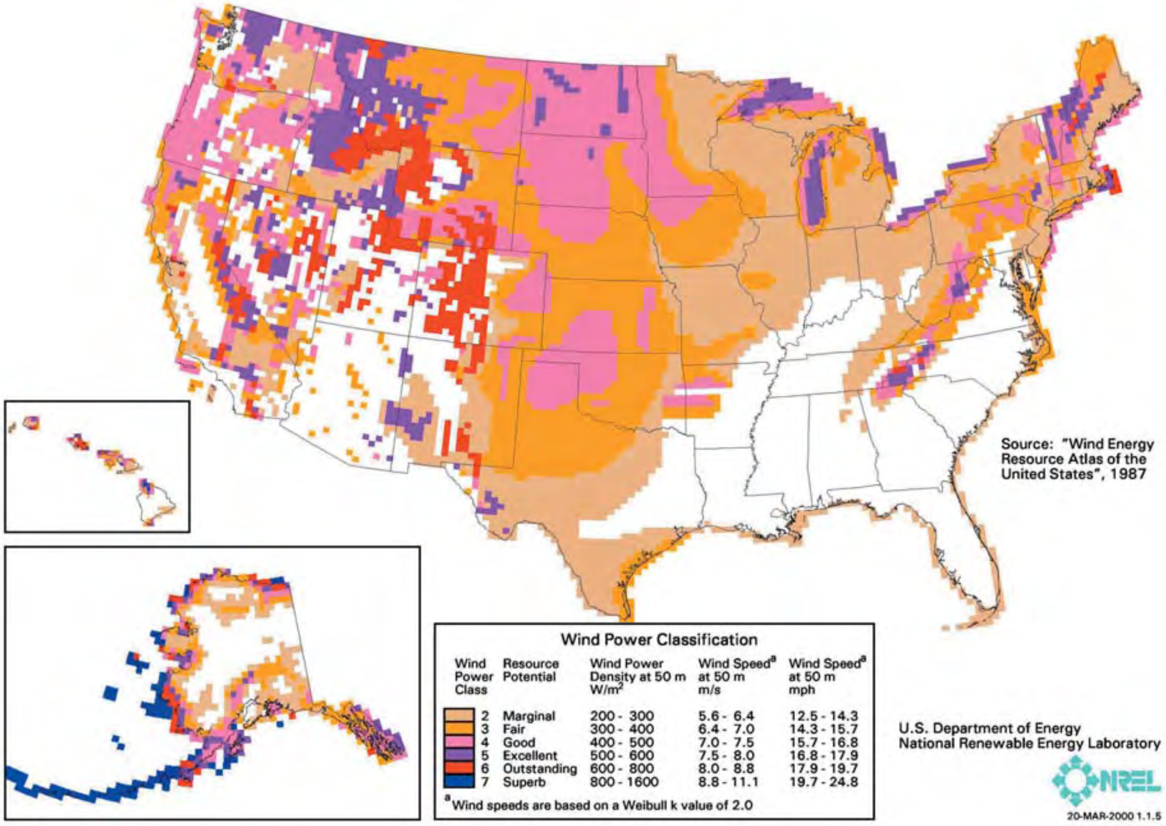


Figure 14. Wind resource map.

States with GIS representations of wind resource and transmission lines and compares the economics of wind to other energy options, selecting the least-cost alternative. The model runs for this study assumed the existing production tax credit of 1.8 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.

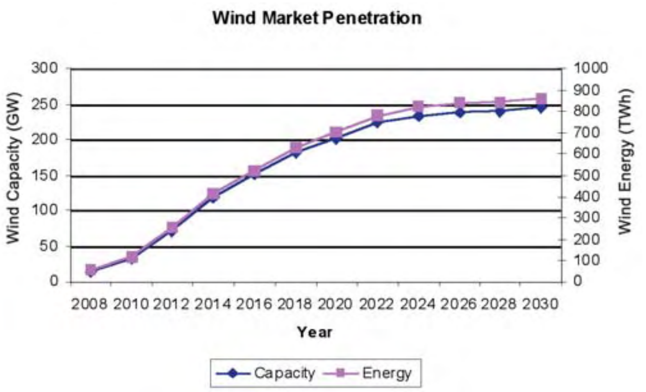


Figure 16. Wind market penetration based on market simulation model.

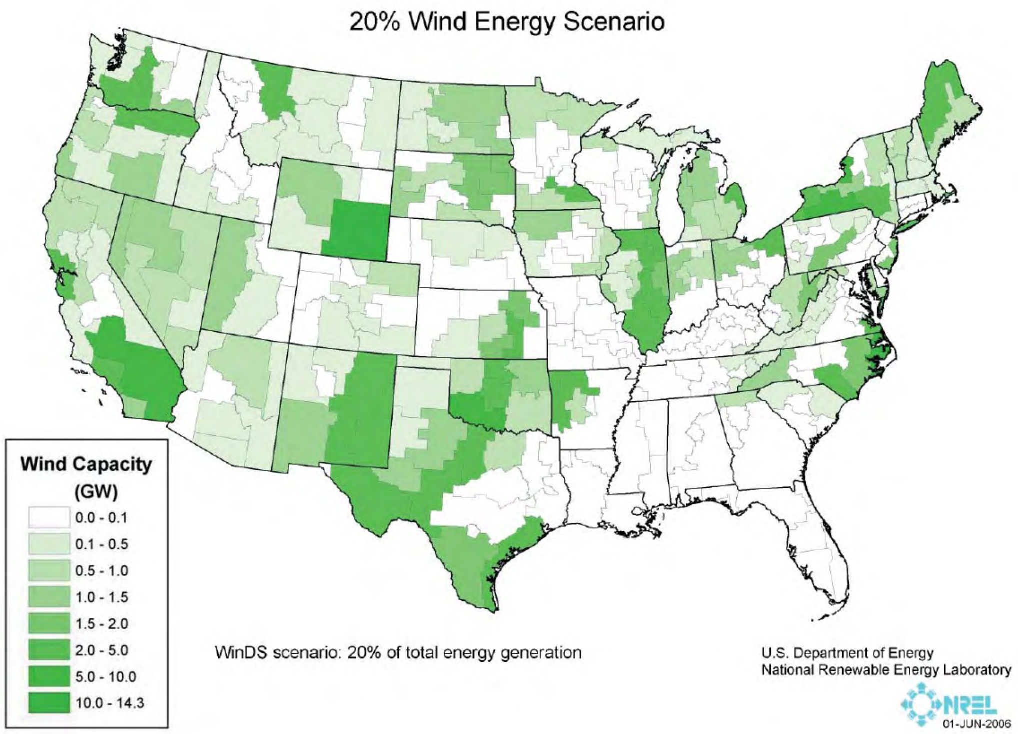


Figure 17. Approximate wind locations for 20% penetration of electric grid (energy) assuming energy efficiency improvements.

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 offset 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.

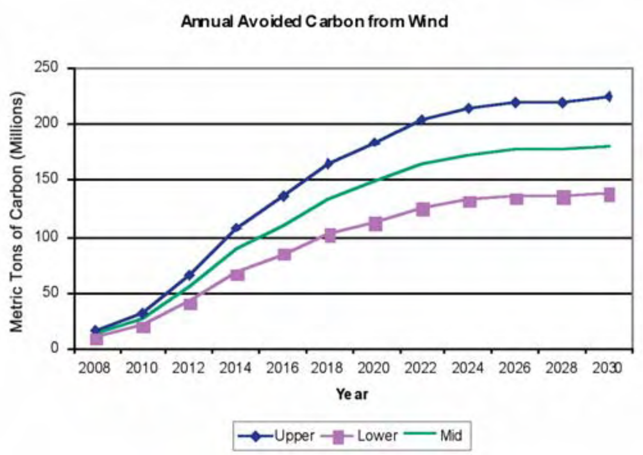


Figure 18. Carbon displacement versus time for the upper, lower, and mid-carbon cases.

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.

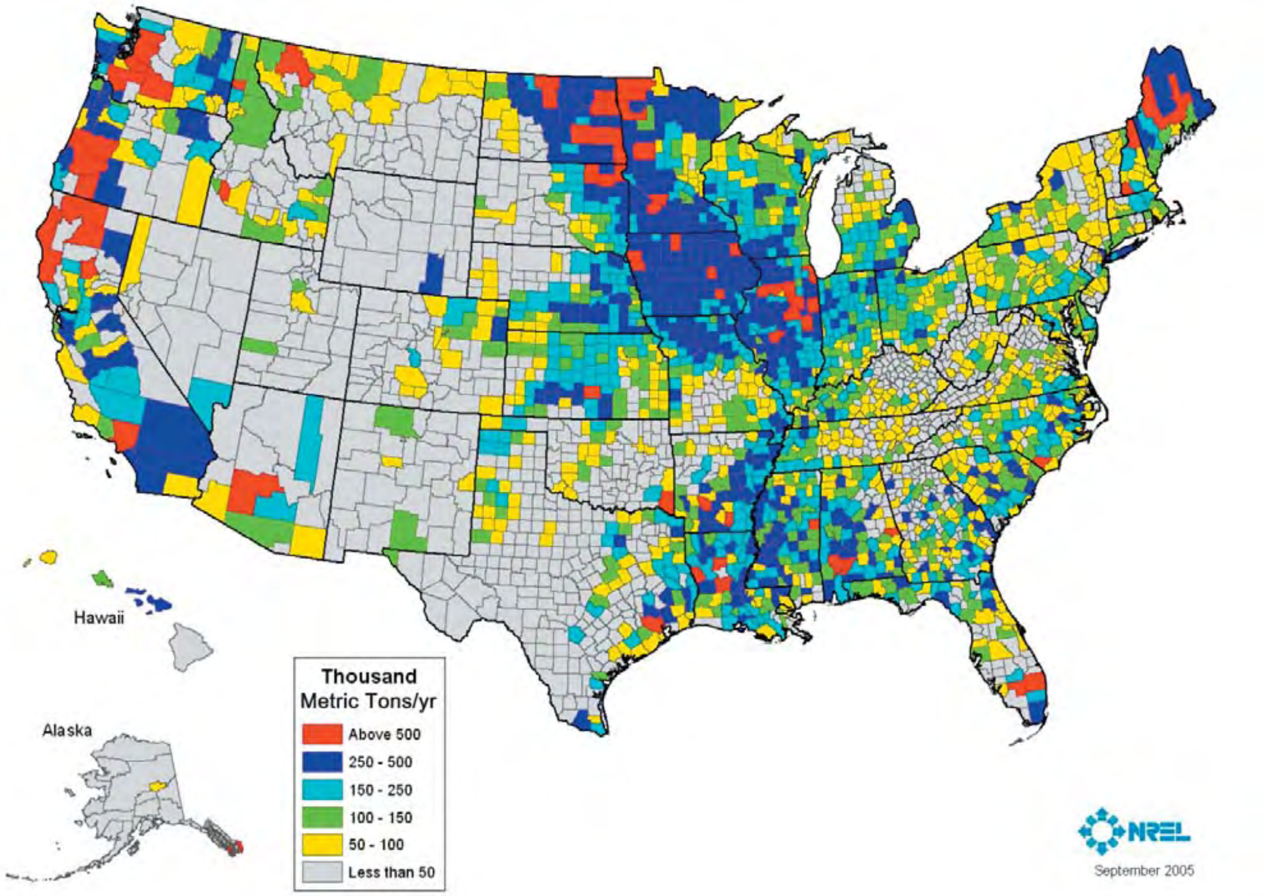


Figure 19. Map of U.S. biomass resource showing dry metric tons of biomass per year for each county.

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 offset 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 offset closer to the higher estimate.

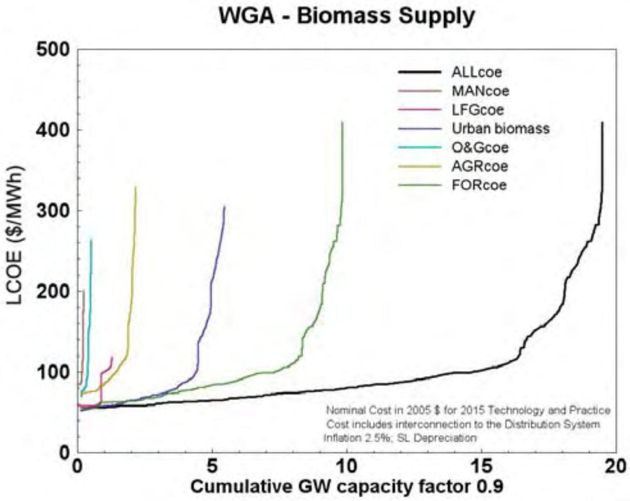


Figure 20. Capacity supply curves for biomass based on 18 Western states. Key to figure curves: Man = Manure, LFG = Landfill Gas, Urban Biomass = Municipal Solid Waste, O&G = Orchard and Grapes (California only), AGR = Agricultural Residues, FOR = Forestry Resources.

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 offset 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: Large array: Aspen Skiing Co.; Smaller photos, top to bottom: Dave Parsons; Pacific Gas & Electric; Warren Gretz

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.

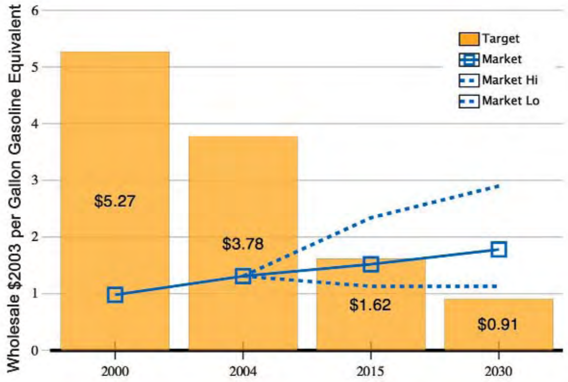


Figure 21. Target costs of cellulosic ethanol from fermentation.

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.

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.

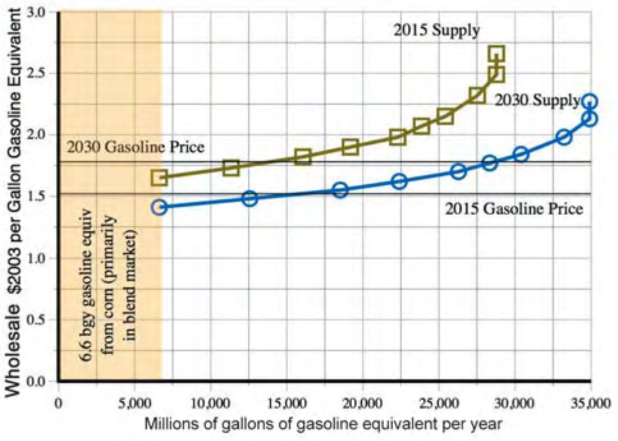


Figure 22. Cellulosic ethanol supply curves for 2015 and 2030 as a function of wholesale prices per gallon of gasoline equivalent.

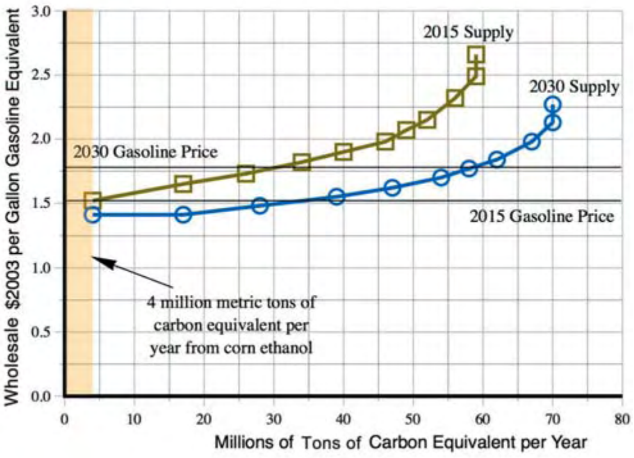


Figure 23. Carbon saving supply curves for cellulosic ethanol for 2015 and 2030.

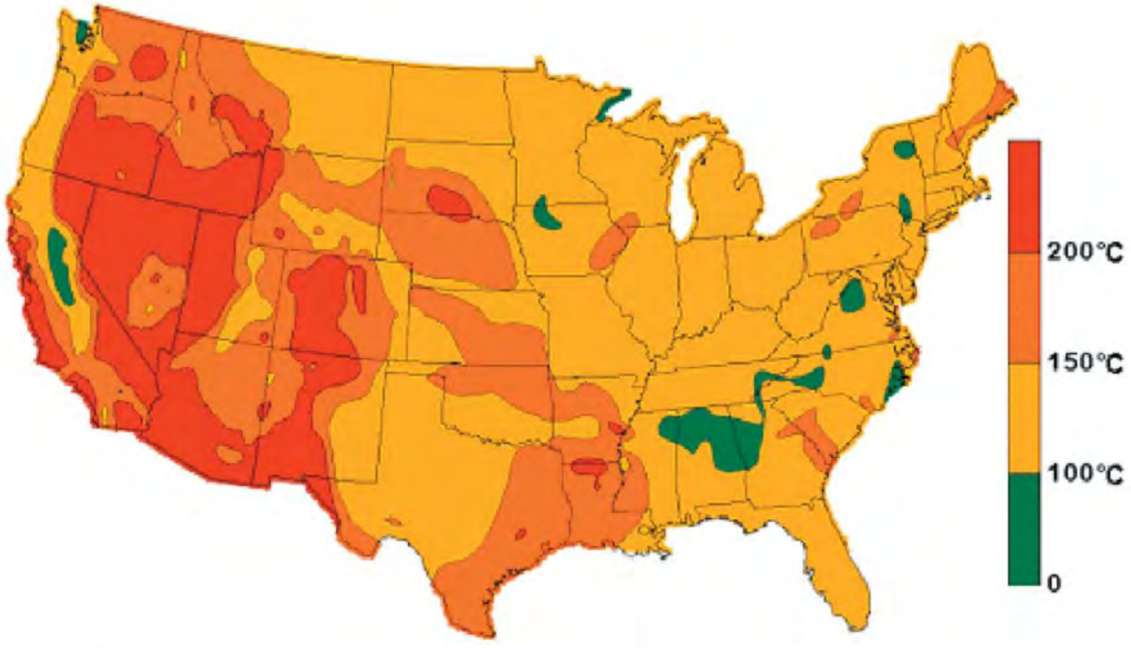
Geothermal Energy

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



Source: Blackwell, Southern Methodist University, 2004.

Figure 24. Temperatures at 6-km depth.

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
LCOE — as of 2010	4.9	
LCOE — as of 2040		5.5

Supply curves are shown in Figure 25.

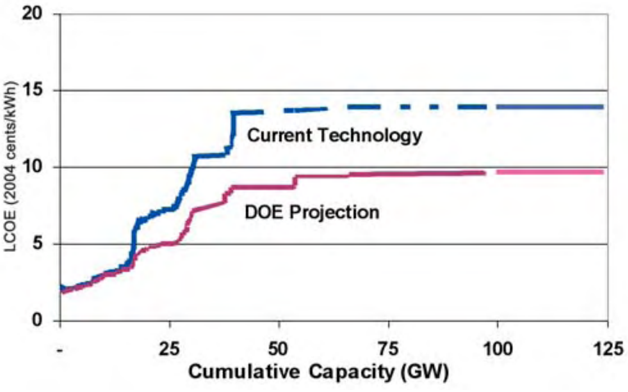


Figure 25. Geothermal supply curves.

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 PV 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 effiiciency 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 offset. 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 offset of 183 MtC/yr, and 41% of this yields 75 MtC/yr.

Table 2 summarizes the various contributions. 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 renewables. Energy effi-

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.

ciency 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.
Carbon offset contributions (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

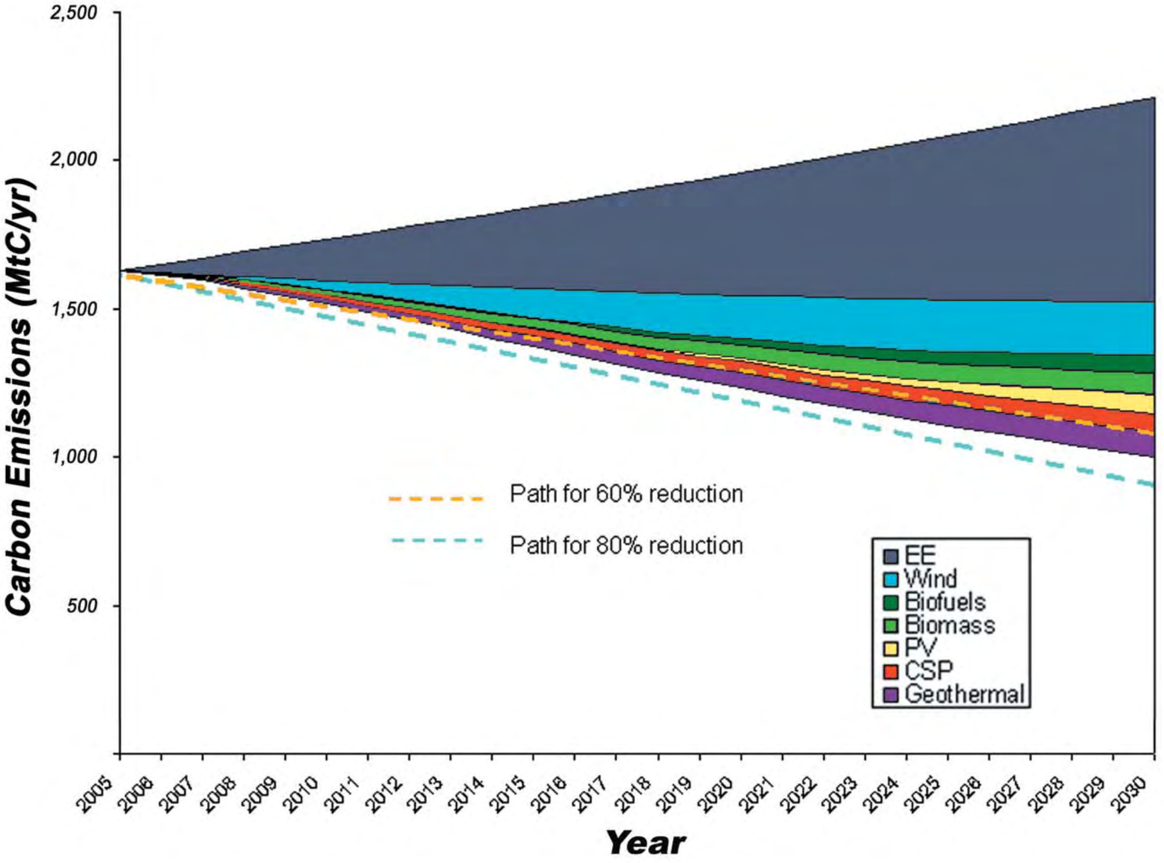


Figure 26. Carbon offset contributions in 2030 from energy efficiency and renewable technologies and paths to achieve reductions of 60% and 80% below today's emissions value by 2050.

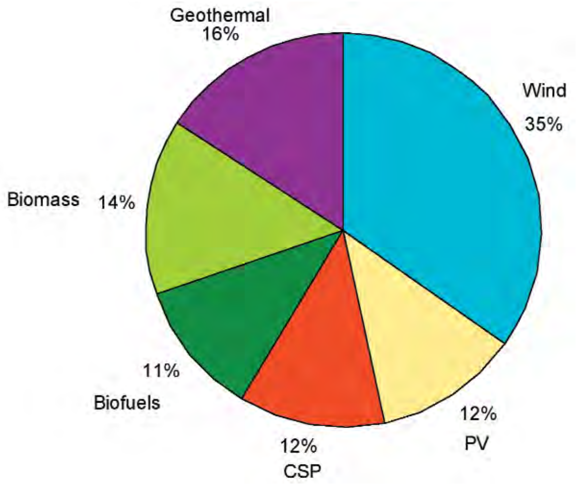


Figure 27. Pie chart showing relative contributions of the various renewables in 2030.

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 offsets 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 will 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 the commonly stated goal of "30% by 2030," but such estimates probably don't 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 amount may 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 deployed 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 offsets. 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 of 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 potentially allow greater carbon offsets in 2030 than we estimated in this report.

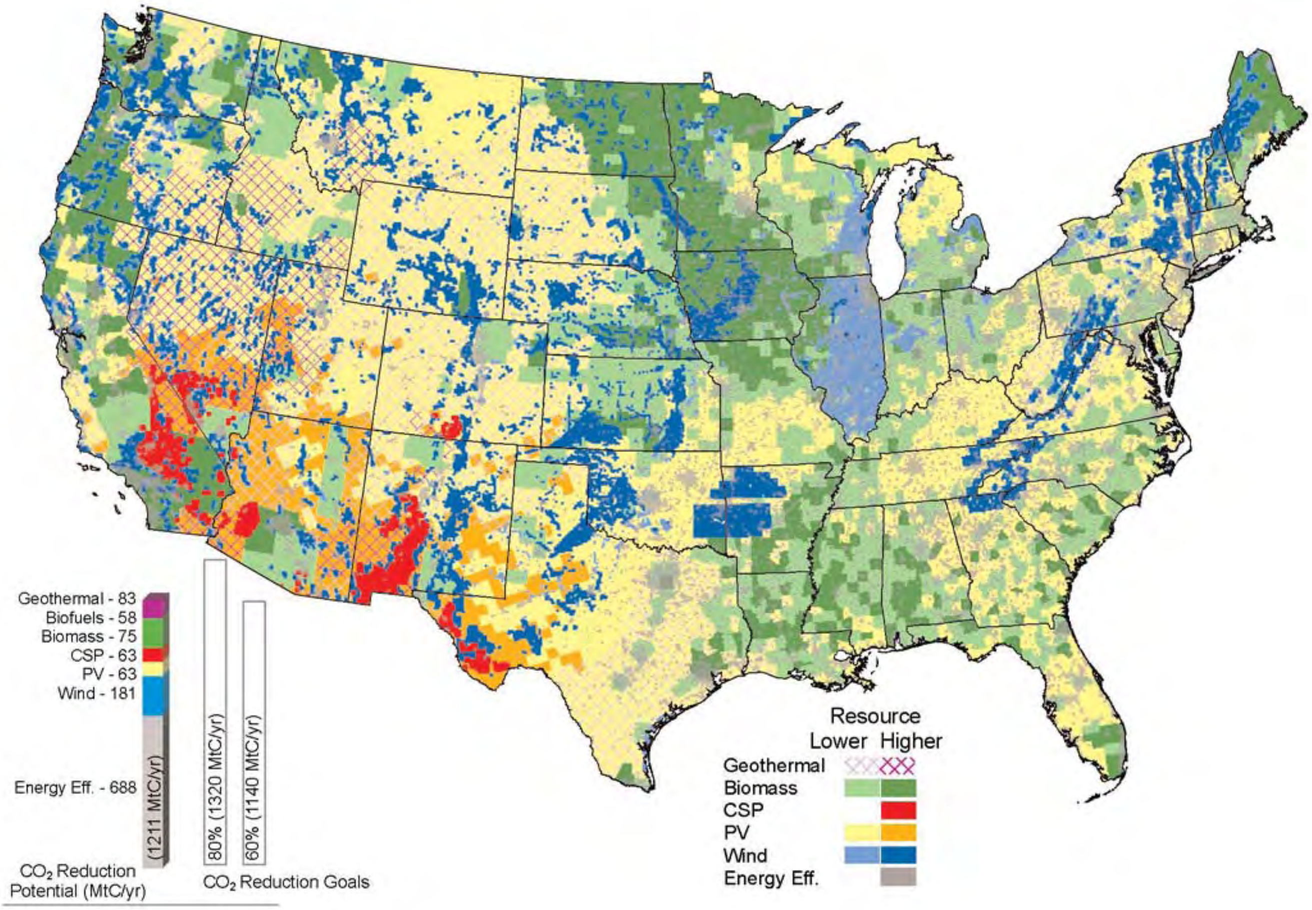


Figure 28. U.S. map indicating the potential contributions by energy efficiency and renewable energy by 2030. CSP and wind are based on deployment scenarios; other renewables indicate resource location.

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 offset 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 values 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 improved nuclear fuel cycles, 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.

References

Additional references appear at the end of each study

Breeze, P., *Power Generation Technologies*, Newnes, Oxford, UK, 2005.

Brown, M.A., Southworth, F., and Stovall T. *Towards a Climate-Friendly Built Environment*, Pew Center on Global Climate Change, Arlington, Virginia, 2005.

Energy Information Administration, *Annual Energy Outlook 2006*, DOE/EIA-0383(2006), February 2006, available at http://www.eia.doe.gov/oiaf/archive/aeo06/index.html

Interlaboratory Working Group, *Scenarios for a Clean Energy Future*, ORNL/CON-476, 2000.

Pacala, S. and Socolow, R., "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science*, Vol. 305, pp. 968-971, 13 August, 2004.

Western Governors' Association, Clean and Diversified Energy Reports, available at http://www.westgov.org/wga/initiatives/cdeac/cdeac-reports.htm

Tackling Climate Change in the U.S.

Potential Carbon Emissions Reductions from 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 (165×10^{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

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.

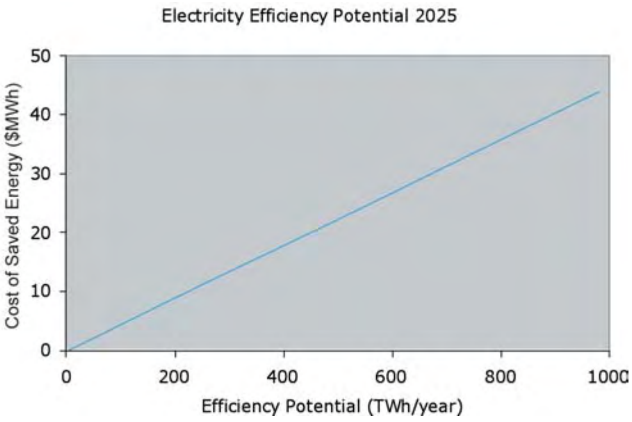


Figure 1. Electric efficiency cost curve (2025).

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.

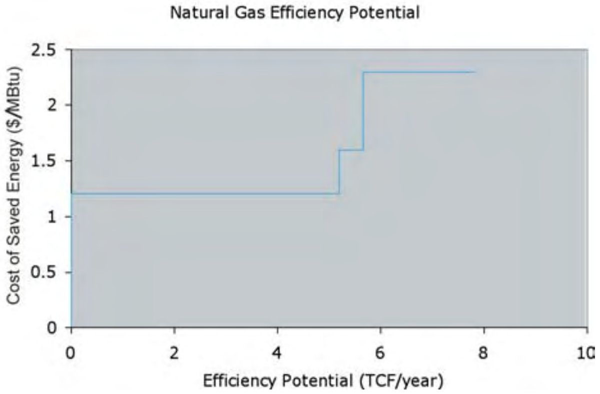


Figure 2. Natural gas efficiency cost curve (2025).

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.

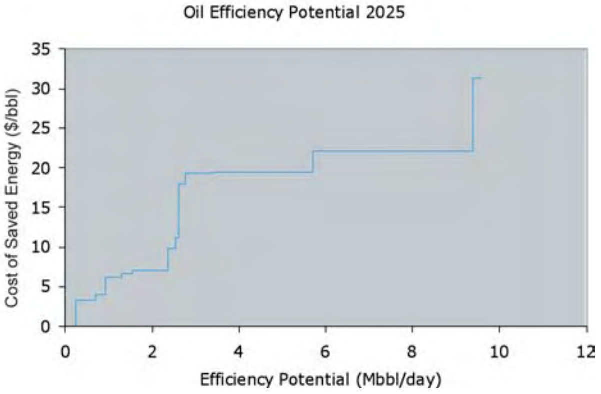


Figure 3. Petroleum efficiency cost curve (2025).

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.

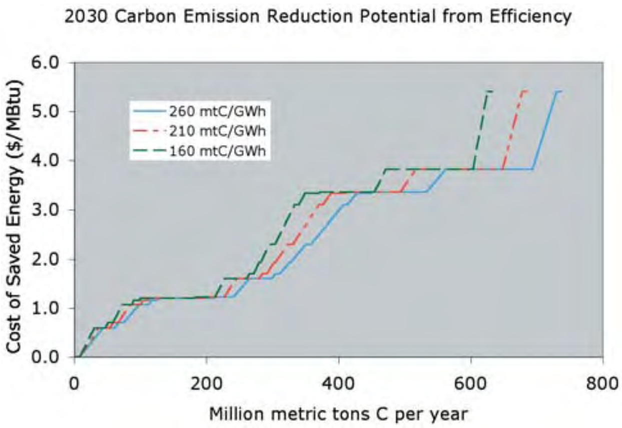


Figure 4. Carbon reduction cost curve based on energy efficiency potential by 2030.

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

The analysis in this paper is based on research conducted at Rocky Mountain Institute with the support of the William and Flora Hewlett Foundation, the Henry Luce Foundation, the Rose Family Foundation, and anonymous private donors.

References

1. U.S. Department of Energy, Energy Information Administration, *Annual Energy Review 2004*.
2. J. N. Swisher, "Regulatory and Mixed Policy Options for Reducing Energy Use and Carbon Emissions," *Mitigation and Adaptation Strategies for Global Change*, vol. 1, pp. 23-49, 1996.
3. A. Meier, et al., *Supplying Energy through Greater Efficiency*, University of California Press, Berkeley, 1983.
4. J. N. Swisher, G. Jannuzzi and R. Redlinger, *Tools and Methods for Integrated Resource Planning*, United Nations Environment Programme (UNEP) Collaborating Centre on Energy and Environment, Risø National Lab, Roskilde, Denmark, 1998.
5. Interlaboratory Working Group, Scenarios for a Clean Energy Future, ORNL/CON-476, 2000.
6. A. B. Lovins, et al. *Winning the Oil Endgame*. Rocky Mountain Institute, Snowmass, Colorado, 2004.
7. See www.architecture2030.org

Tackling Climate Change in the U.S.

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

Appendix

An exploding population of human beings 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 Charles 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 humankind is 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 human beings 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.

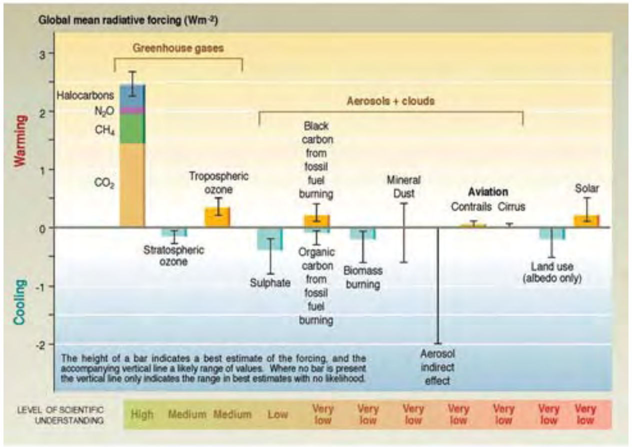


Figure 1. Radiative forcing sources. Carbon dioxide is the largest positive forcing and methane is second. (Source: IPCC Third Assessment Report, 2001.)

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.

(More recent ice cores samples have extended this result all the way 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.

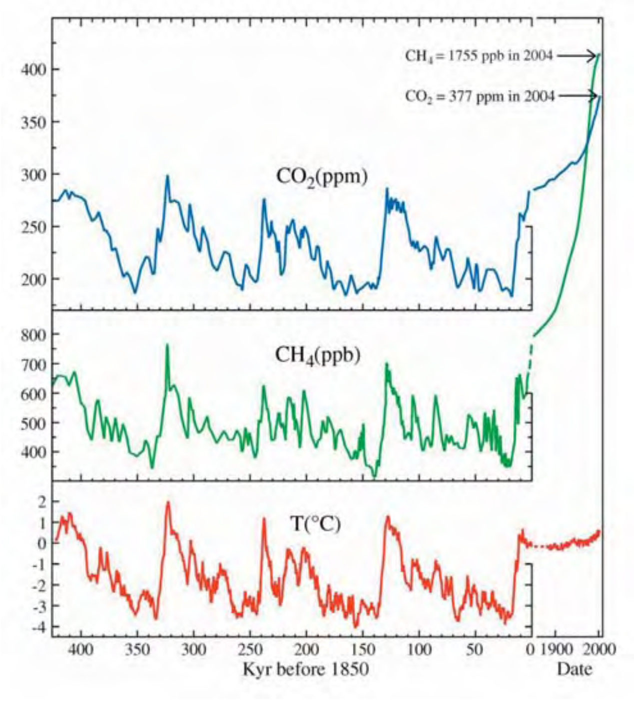


Figure 2. Paleoclimatic data from ice cores. Note the unprecedented recent increases in carbon dioxide and methane. The temperature, though increasing, has not yet reached record levels but will likely do so by mid-century. (Source: Hansen, Clim. Change, 68, 269, 2005.)

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 population of human beings who are 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 the normal 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

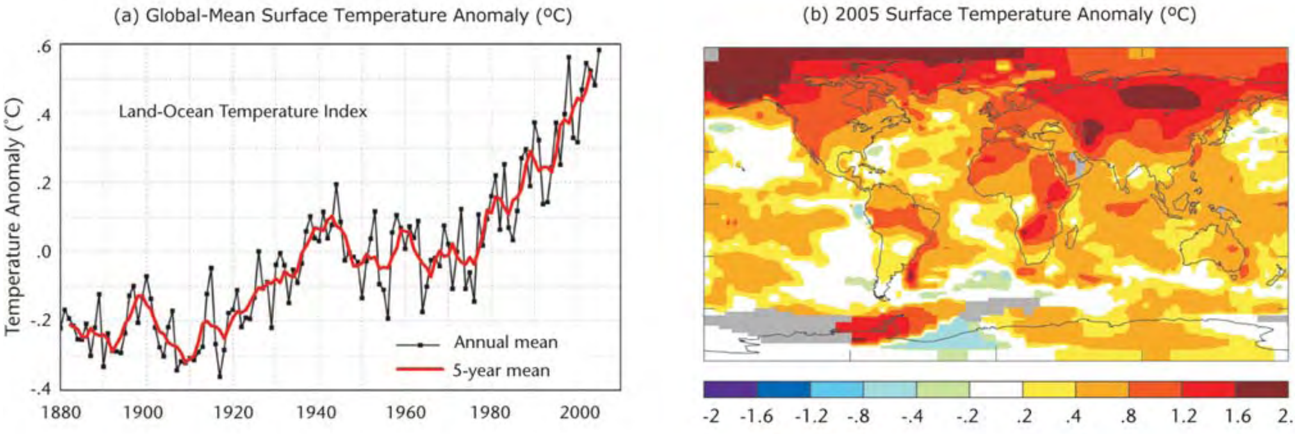


Figure 3. a) Details of global mean surface temperature measurements since 1880. 2005 had the highest global temperature ever recorded. b) The Arctic region has experienced the biggest temperature increases. (Source: Goddard Institute for Space Studies)

them are shrinking, and their disappearance will result in severe water shortages for millions of people.

Global warming is also expected to increase the strength of El Niño events that warm the Pacific resulting in more so-called "super El Niño" 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 the planet 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 U.S. is responsible for 23% of the world's CO_2 emissions, yet has only 5% of the world's population.

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 emissions 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 percent 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.

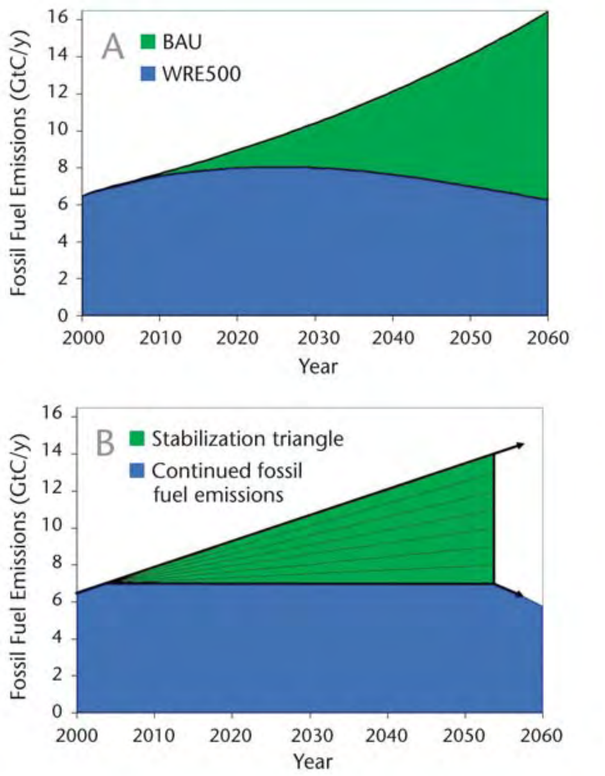


Figure 4. Illustration of A) the business-as-usual and carbon reduction curves and B) the idealized Pacala-Socolow "wedges" approach to describing needed world carbon emissions reductions. Carbon-free energy sources must fill the gap between business-as-usual (BAU) emissions growth and the path needed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

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.

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 tiny 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 cars are hooked into the grid and if electricity flows to and from the grid (as is the case with many PV installations), 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.

Published by the
American Solar Energy Society
United States Section of the International Solar Energy Society

The American Solar Energy Society is the nation's oldest and largest membership society dedicated to advancing the US toward a sustainable energy economy. ASES publishes *SOLAR TODAY* magazine, organizes the annual National Solar Tour, sponsors the National Solar Energy Conference and advocates for government policy initiatives to promote the research and deployment of renewable energy. ASES has regional and state chapters throughout the country. **www.ases.org**

American Solar Energy Society
WORKING TOWARD A SUSTAINABLE ENERGY FUTURE

ISBN 0-89553-306-5