policy

Final Proceedings of the Pew Center/NCEP Workshop on

The 10-50 Solution

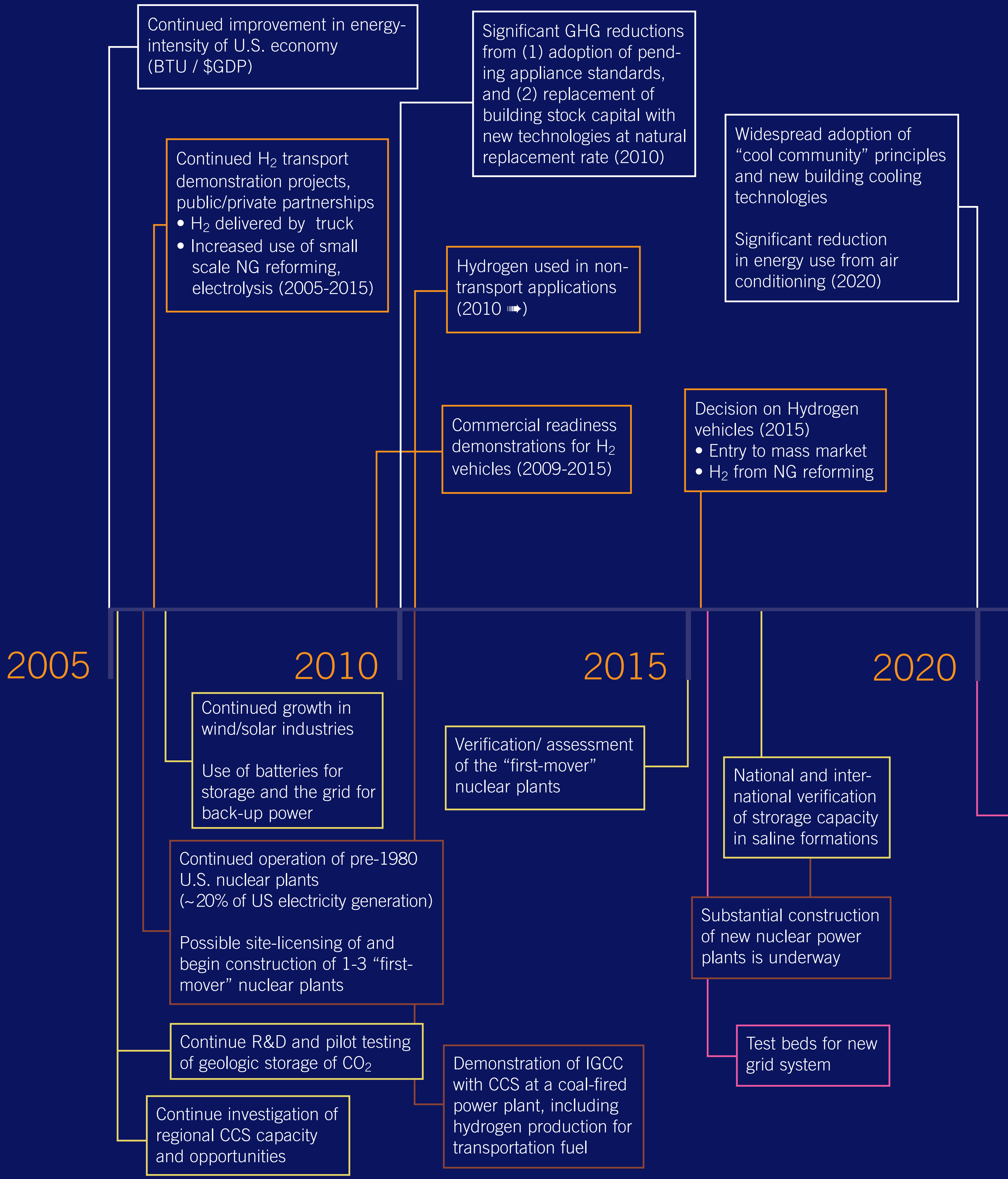
Technologies and Policies for a Low-Carbon Future

The St. Regis Hotel
Washington, DC
March 25-26, 2004

technology

PEW CENTER
ON
Global CLIMATE CHANGE

NATIONAL COMMISSION ON ENERGY POLICY



Continued improvement in energy-intensity of U.S. economy (BTU / $GDP)

Significant GHG reductions from (1) adoption of pending appliance standards, and (2) replacement of building stock capital with new technologies at natural replacement rate (2010)

Widespread adoption of "cool community" principles and new building cooling technologies

Significant reduction in energy use from air conditioning (2020)

Continued H_2 transport demonstration projects, public/private partnerships
- H_2 delivered by truck
- Increased use of small scale NG reforming, electrolysis (2005-2015)

Hydrogen used in non-transport applications (2010 ➠)

Commercial readiness demonstrations for H_2 vehicles (2009-2015)

Decision on Hydrogen vehicles (2015)
- Entry to mass market
- H_2 from NG reforming

2005

2010

2015

2020

Continued growth in wind/solar industries

Use of batteries for storage and the grid for back-up power

Verification/ assessment of the "first-mover" nuclear plants

National and international verification of strorage capacity in saline formations

Continued operation of pre-1980 U.S. nuclear plants (~20% of US electricity generation)

Possible site-licensing of and begin construction of 1-3 "first-mover" nuclear plants

Substantial construction of new nuclear power plants is underway

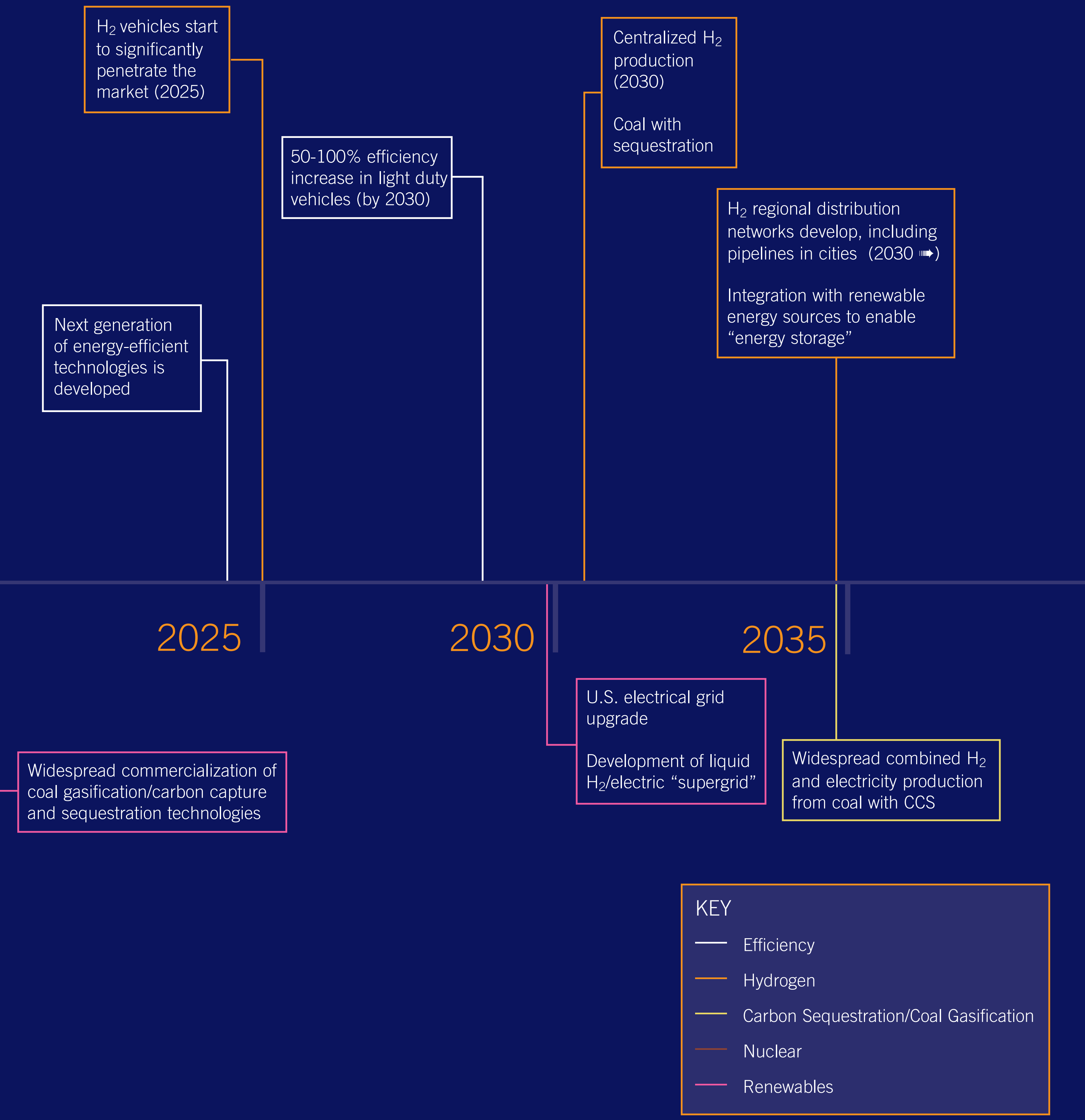
Test beds for new grid system

Continue R&D and pilot testing of geologic storage of CO_2

Demonstration of IGCC with CCS at a coal-fired power plant, including hydrogen production for transportation fuel

Continue investigation of regional CCS capacity and opportunities

Figure 1: Low-Carbon Technological Options – Status and Potential



H_2 vehicles start to significantly penetrate the market (2025)

50-100% efficiency increase in light duty vehicles (by 2030)

Centralized H_2 production (2030)

Coal with sequestration

H_2 regional distribution networks develop, including pipelines in cities (2030 ➠)

Integration with renewable energy sources to enable “energy storage”

Next generation of energy-efficient technologies is developed

2025

2030

2035

U.S. electrical grid upgrade

Development of liquid H_2/electric “supergrid”

Widespread combined H_2 and electricity production from coal with CCS

Widespread commercialization of coal gasification/carbon capture and sequestration technologies

KEY

— Efficiency

— Hydrogen

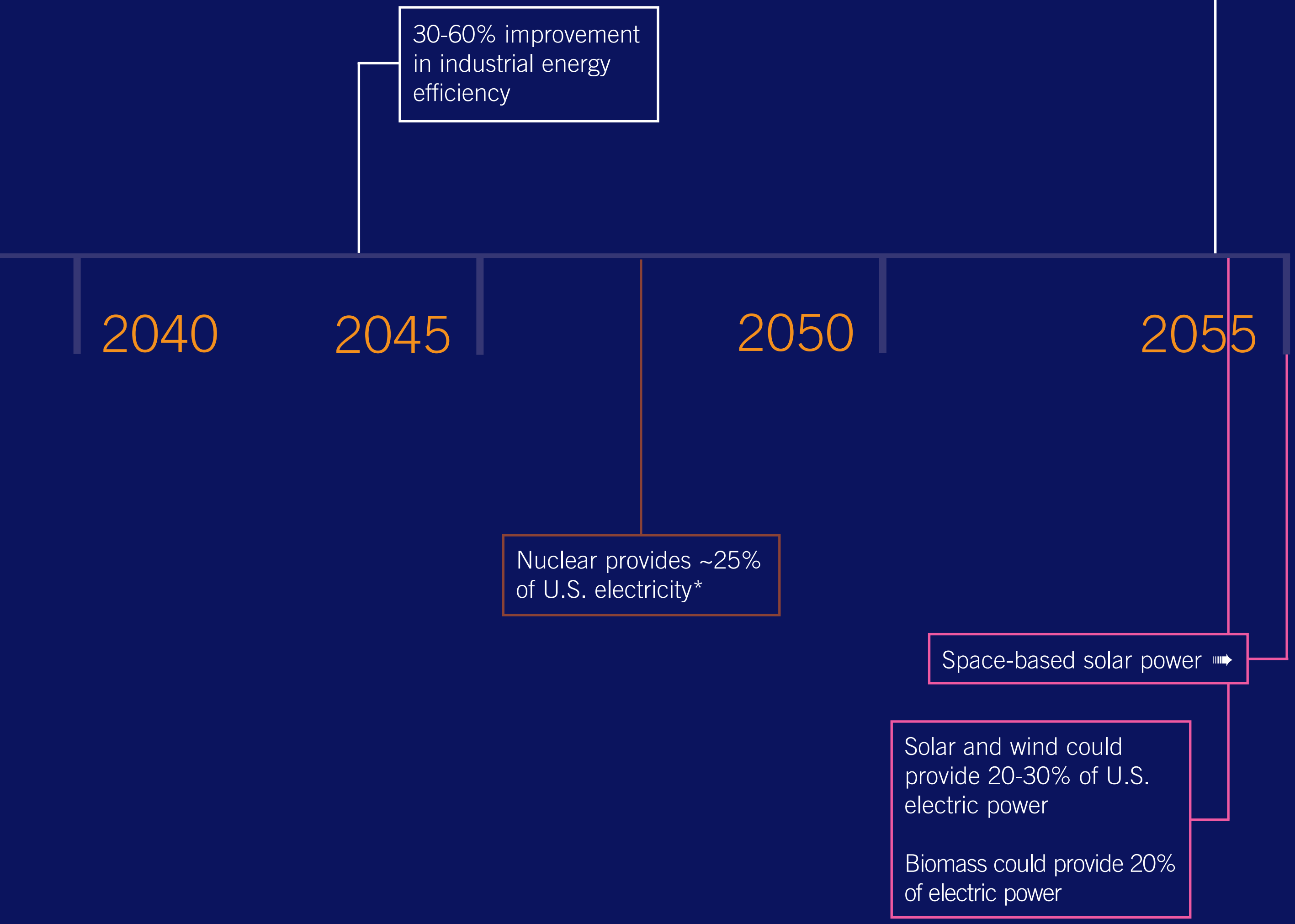
— Carbon Sequestration/Coal Gasification

— Nuclear

— Renewables

*If the “first-mover” problem is solved, as well as safety, cost, non-proliferation, and public acceptance.

The technological options available to enable a low-carbon future will continue to develop over time and will depend upon technological progress and investments made in the near term



2040

2045

2050

2055

Buildings as net energy exporter

30-60% improvement in industrial energy efficiency

Nuclear provides ~25% of U.S. electricity*

Space-based solar power ➠

Solar and wind could provide 20-30% of U.S. electric power

Biomass could provide 20% of electric power

WORKSHOP PROCEEDINGS

The 10-50 Solution

Technologies and Policies for a Low-Carbon Future

MARCH 25-26, 2004

WASHINGTON, DC

Pew Center on Global Climate Change
2101 Wilson Blvd., Suite 550
Arlington, VA 22201

The National Commission on Energy Policy
1616 H Street, NW, 6th Floor
Washington, DC 20006

Contents

FOREWORD

The Pew Center on Global Climate Change and the National Commission on Energy Policy (NCEP) are pleased to present the proceedings of our March 2004 workshop, *The 10-50 Solution: Technologies and Policies for a Low-Carbon Future*. In order to tackle a problem as multi-faceted and complex as climate change, policy-makers and business leaders must catalyze both short-term (within this decade – "10" year) and long-term (e.g., "50" year) solutions.

Technology will play a critical role in enabling a low-carbon future. The "10-50 Solution" workshop brought together over 100 invited policy-makers, business leaders, NGO representatives, and leading experts to examine technologies that are likely to play a key role in addressing the climate change challenge over the next 50 years, as well as the policies that will be needed to push and pull these and other emerging technologies into the marketplace. This volume includes the background papers commissioned for the workshop as well as presentations on opportunities in industry made during the course of our meeting. While the workshop was structured around five emerging technologies, the lessons learned can be applied more broadly.

Significant uncertainties remain about what a low-carbon future may look like and the role of specific technologies and policies in contributing to such a future. Yet, despite these uncertainties, one thing is clear: We need to start now enacting sensible policies and making investments in order to achieve the technological changes necessary over the next five decades.

We hope that these proceedings will provide critical analysis of some key technology and policy options to inform the nation's dialogue about a low-carbon future. We also hope that they will lay the groundwork for a sustained, 50-year effort to reduce greenhouse gas emissions. We extend our appreciation to all of the workshop speakers and participants, and especially to the background paper authors, who helped make the workshop a success.

Eileen Claussen
President
Pew Center on Global Climate Change

Jason Grumet
Executive Director
National Commission on Energy Policy

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List of Participants

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PEW CENTER ON Global CLIMATE CHANGE

NATIONAL COMMISSION ON ENERGY POLICY

The 10-50 Solution
Technologies and Policies
for a Low-Carbon Future

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Sally Benson, Lawrence Berkeley National Laboratory
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Marilyn Brown, NCEP Commissioner/Oak Ridge National Laboratory
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Thomas Cochran, Natural Resources Defense Council
Jon Davis, Rio Tinto
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Daniel Kammen, University of California-Berkeley
Melanie Kenderdine, Gas Technology Institute
Marilyn Kray, Exelon Corporation
Mark Levine, Lawrence Berkeley National Laboratory
Amory Lovins, Rocky Mountain Institute
Vivian Loftness, Carnegie Mellon University
Joan MacNaughton, Department of Trade & Industry (UK)
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Chris Mottershead, BP
Gene Nemanich, National Hydrogen Association/Chevron-Texaco (retired, 2003)
Richard Newell, Resources for the Future
Joan Ogden, University of California-Davis
Lynn Price, Lawrence Berkeley National Laboratory
Robert Prolman, Weyerhaeuser Company
Bill Reilly, NCEP Commissioner/Aqua International Partners
Venki Raman, Air Products & Chemicals, Inc.
Mike Schwartz, Ford Motor Company
Phil Sharp, NCEP Commissioner/Lexecon, Inc./Van Ness Feldman
Dale Simbeck, SFA Pacific, Inc.
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R. James Woolsey, NCEP Commissioner/Booz Allen Hamilton
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James Dooley, Battelle Memorial Institute

Chris Edwards, Stanford University

The Honorable Rodney Ellis, NCEP Commissioner/Texas State Senator

William Ellis, Yale University

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Robert Friedman, Institute for Biological Energy Alternatives

Kelly Sims Gallagher, Harvard University

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Michael Grubb, Carbon Trust/Imperial College (UK)

David Hawkins, Natural Resources Defense Council

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Sasha Mackler, National Commission on Energy Policy

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Chris Miller, Senate Environment & Public Works Committee

Michael Mudd, American Electric Power

William Nitze, Gemstar Group, Inc.

Peter O'Connor, Global Environment & Technology Foundation

Jonathan Pershing, World Resources Institute

Wandile Phakathi, Texas State Legislature

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Billy Pizer, National Commission on Energy Policy

Paul Portney, Resources for the Future

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Tracy Terry, National Commission on Energy Policy

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Brennen Walsh, National Commission on Energy Policy

Kathleen Welch, The Pew Charitable Trusts

Robert Williams, Princeton University

James Wolf, Independent consultant

Franz Wuerfmannsdobler, Office of U.S. Senator Robert C. Byrd

Brent Yacobucci, Congressional Research Service

Kurt Yeager, Electric Power Reseach Institute

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Workshop Agenda

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PEW CENTER ON Global CLIMATE CHANGE

National Commission on Energy Policy

The 10-50 Solution

Technologies and Policies
for a Low-Carbon Future

MARCH 25-26, 2004
ST. REGIS HOTEL
WASHINGTON, DC

WORKSHOP AGENDA

Thursday, March 25th

9:30 am – Noon

OPENING SESSION

Welcome and Opening Address
William Reilly, NCEP Tri-Chair; President and CEO, Aqua International Partners; former Administrator of the U.S. Environmental Protection Agency (1989-1993)

Why 10-50? An Energy Security Perspective
R. James Woolsey, NCEP Commissioner; Vice President, Booz, Allen, Hamilton; former Director of Central Intelligence

Why 10-50? A Climate Perspective
Eileen Claussen, President, Pew Center on Global Climate Change

The UK's Energy Strategy to 2050
Joan MacNaughton, Director General, Energy Group, Dept. of Trade & Industry (UK)

Noon - 1:30 pm

LUNCH - OPPORTUNITIES IN INDUSTRY

Is it possible to de-couple growth in key business sectors over the next 50 years from growth in carbon emissions resulting from business activities?

Session Chair: Geoffrey Heal, Columbia Business School

Presenters:
Pat Atkins, Alcoa
Chris Mottershead, BP
Robert Wimmer, Toyota Motors North America
Bob Prolman, Weyerhaeuser

1:30 pm - 4:45 pm

EFFICIENCY, HYDROGEN, AND CARBON SEQUESTRATION/COAL GASIFICATION

What technological progress is needed now and in the next 50 years? What policies are needed in the near, medium, and long term to push and pull technology into the market?

Session Chair: Susan Tierney, NCEP Commissioner; Managing Principal, The Analysis Group; former Assistant Secretary of Energy for Policy, U.S. Department of Energy

Commentator: Melanie Kenderdine, Vice President, Gas Technology Institute

1:30 pm - 4:45 pm

EFFICIENCY, HYDROGEN, AND CARBON SEQUESTRATION/COAL GASIFICATION (continued)

Authors/Contributors:

Efficiency:

Gilbert Metcalf, Tufts University (Overview)
Vivian Loftness, Carnegie Mellon University
Richard Newell, Resources for the Future
*Lynn Price and Ernst Worrell, Lawrence Berkeley National Laboratory
(*Mark Levine, LBNL, presented)

Hydrogen:

Joan Ogden, UC-Davis (Overview)
David Greene, Oak Ridge National Laboratory
Gene Nemanich, National Hydrogen Association
Venki Raman, Air Products and Chemicals
Mike Schwarz, Ford Motor Company

Carbon Sequestration/Coal Gasification:

Sally Benson, Lawrence Berkeley National Laboratory (Overview)
Dale Simbeck, SFA Pacific, Inc.
Jon Davis, Rio Tinto
Robert Burruss, United States Geological Survey

6:00 pm

RECEPTION

7:00 pm

DINNER

Keynote Address: Good News About Profitable Climate Solutions

Amory Lovins, CEO, Rocky Mountain Institute

Friday, March 26th

8:30 am - 10:30 am

ADVANCED NUCLEAR GENERATION AND RENEWABLES

What technological progress is needed now and in the next 50 years? What policies are needed in the near, medium, and long term to push and pull technology into the market?

Session Chair: Phil Sharp, NCEP Congressional Chair; Senior Advisor, Lexecon, Inc.; Senior Policy Advisor, Van Ness Feldman; Former U.S. Representative, IN

Commentator: Marilyn Brown, NCEP Commissioner; Director, Energy Efficiency and Renewable Energy Program, Oak Ridge National Laboratory

Authors/Contributors:

Advanced Nuclear Generation:

Ernest Moniz, Massachusetts Institute of Technology (Overview)
Thomas Cochran, Natural Resources Defense Council
Marilyn Kray, Exelon Corporation

8:30 am - 10:30 am

ADVANCED NUCLEAR GENERATION AND RENEWABLES (cont'd)

Renewables:
Martin Hoffert, New York University (Overview)
Roger Anderson, Columbia University
Gene Berry, Lawrence Livermore National Laboratory
Dan Kammen, UC-Berkeley

10:30 am – 11:00 am

BREAK

11:00 am – 12:30 pm

INTEGRATING COMMON THEMES

Session Chair: John Holdren, NCEP Tri-Chair; Teresa and John Heinz Professor of Environmental Policy, Harvard University
Session Co-Chair: Judi Greenwald, Director of Innovative Solutions, Pew Center on Global Climate Change
Commentator: Vijay V. Vaitheeswaran, Global Environment & Energy Correspondent, *The Economist*

12:30 pm - 1:30 pm

LUNCH
Keynote Address: John Cahill, Chief of Staff, Governor George E. Pataki (NY)

1:30 pm - 3:00 pm

CROSS-CUTTING POLICY MEASURES
Session Chair: Leslie Carothers, President, Environmental Law Institute
Session Co-Chair: Vicki Arroyo, Director of Policy Analysis, Pew Center on Global Climate Change

3:00 pm - 4:00 pm

CLOSING PLENARY
Observations and Insights: Jason Grumet, Executive Director, National Commission on Energy Policy
The Path Forward: Eileen Claussen, President, Pew Center on Global Climate Change

Copies of workshop presentations are available at www.pewclimate.org.

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Executive Summary

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PEW CENTER ON Global CLIMATE CHANGE

National Commission on Energy Policy

Executive Summary: The ”10-50” Solution

Addressing the challenge of global climate change will require a significant reduction in annual greenhouse gas (GHG) emissions in the United States and throughout the world—by 2050. This will require a fundamental shift from an economy predominantly based on fossil fuels to one based on efficiently managed low-carbon energy sources and technologies that capture and store carbon from fossil fuels. Such a transition could also have other benefits, including increased energy security, improved public health, and increased economic development. But the transition will not be easy, as significant technological challenges, social and economic concerns, and political constraints exist.

Achievement of this transition depends on both near-term and long-term actions. In the near term, it is essential to take advantage of current technologies and opportunities, and also to make substantial investments in the technologies of the future. But most of all, the United States needs a clearly enunciated policy. Without such a policy, businesses, consumers, and citizens are missing opportunities for cost-effective GHG reductions and investment for the future. Too often the debate over GHG emission reductions pits near-term actions against long-term investments in technology, when in fact both are necessary and are each more effective if undertaken together. A variety of policies, public and private leadership, and broad societal engagement will be needed to bring low-carbon technologies into the market. Because of the long-lived nature of most energy infrastructure, it is critical that action begin now to promote the development and use of low-carbon energy technologies.

The Pew Center on Global Climate Change and the National Commission on Energy Policy (NCEP) recently held a conference to address both near-term and long-term challenges and opportunities in attaining a low-carbon future—“The 10-50 Solution: Technologies and Policies for a Low-Carbon Future.” The title reflects the need to initiate policies and conduct research within this decade (“10”), but also to sustain policies and promote research, development, and deployment (RD&D) of new technologies over the next half-century (“50”).

In preparation for the workshop, the Pew Center and NCEP commissioned analyses—in the form of overview and contributing papers—in five key areas: efficiency, hydrogen, carbon sequestration/coal gasification, advanced nuclear technologies, and renewables. In addition to exploration of these key technologies, the workshop featured discussions of opportunities in industry to reduce GHG emissions from processes and products, the role of natural gas in the transition to a low-carbon future, and examples of states and other countries enacting climate and clean-energy policy.

Several common themes and cross-cutting and technology-specific policy recommendations emerged from the workshop and the background papers. A brief discussion of these themes and policy recommendations is below.

Common Themes and Policy Recommendations

- *Clear and consistent policy signals are urgently needed*. Both broad (economy-wide) and technology-specific policies are essential. There is also a need to balance policy flexibility with reasonable policy certainty. A sustained carbon price signal—through policies such as cap-and-trade or carbon taxes—was identified as the most important cross-cutting policy driver by a number of participants. While such a program is being developed, an important first step would be mandatory GHG emission reporting—an essential tool for identifying and stimulating reductions.

- *A portfolio of technologies and policies will be needed to drive the absolute reductions of GHG emissions necessary to address climate change.* No single technology or policy will be sufficient to enable a low-carbon future by 2050. All of the technologies studied have the potential to enable significant GHG reductions, yet increased and revamped RD&D is necessary in all of them. Efficiency will provide the greatest opportunity in the near term and will remain important over the long term as well. In addition, natural gas can play a key role in the transition to a low-carbon future, subject to price and supply constraints. While specific technologies are likely to be important players, it is important to avoid the temptation to pick "winners." The challenge is to design policies that are neutral enough to promote the development and deployment of a suite of low-carbon technologies, yet also tailored enough to push and pull some specific technologies that might not enter the market under a broad policy mechanism. Finally, cooperative international efforts can reduce the burden on all countries of developing low-carbon energy technologies.

- *A low-carbon technology revolution will require both leadership and broad engagement throughout society.* Policies should address climate change in the context of other societal goals (e.g., clean air, energy security) thereby taking advantage of co-benefits and creating public/private partnerships and non-traditional "alliances." Leadership is needed in both the public and private sectors, and clear and unambiguous targets set by corporate leaders and governments can have a significant positive effect on achieving GHG reductions. Consumers and citizens must be involved in the transition to a low-carbon economy, and a greater focus on critical energy challenges (both in terms of resources and innovative capacity) is needed from U.S. universities and private-sector research laboratories.

- *It is essential to start now.* Finally, there was broad consensus that it is imperative to begin now with clear statements of policy and both cross-cutting and technology-specific policies and investments in order to achieve a low-carbon economy by 2050.

Technology-Specific Policies

In addition to the widespread support among workshop participants for broad national policies and investments, there was also recognition of the need for “ husbandry” of certain key technologies.

Energy Efficiency

The technological potential for energy efficiency improvements now and in the future is significant, yet this potential is not likely to be realized through market forces alone. Accordingly, policies that address the technical, cost, and societal hurdles facing widespread improvements in energy efficiency are needed. In addition to price signals and reporting, certain standards, incentives, and RD&D programs can increase the use of efficient technologies. These options include :

- adoption and promotion of codes and standards focused on maximizing GHG reductions (e.g., for buildings, vehicles, appliances);
- increases in public RD&D in innovative energy efficiency technologies; and
- incentives for the private and public procurement of highly efficient technologies.

Hydrogen in Transportation

Specific policies are needed to address the major challenges to hydrogen becoming the low-carbon transportation fuel of the future (probably after 2025). Near-term policy options identified to enable future widespread deployment of hydrogen and other potentially low-carbon transportation technologies include:

- continued and increased federal support for hydrogen-related R&D in targeted areas (e.g., low-carbon hydrogen production, storage, and fuel cells);
- national and international harmonization of hydrogen codes and standards;
- continued federal and state government support for, and participation in, public/private partnerships;
- incentives to increase the development and deployment of lower-GHG transportation technologies (e.g., hybrids), many of which are part of an evolutionary path toward the use of hydrogen and fuel cells; and
- increased consumer and public education regarding transportation, energy use, and GHG emissions.

Carbon Sequestration/Coal Gasification

In order to answer critical R&D questions and to commercialize carbon capture and storage by 2025, significant effort must be made over the next 10 to 15 years. Near-term steps include:

- A coordinated international effort to deploy coal gasification with carbon capture and sequestration (CCS) through trial projects that focus on remaining technical issues (e.g., four to six international projects);
- establishment of carbon sequestration trial projects in the United States to validate the integrity of geologic storage (e.g., four such projects);
- removal of policy disincentives to shutting down old coal plants;
- beginning to establish a regulatory framework for underground carbon dioxide (CO_2) storage;
- conducting R&D to reduce the cost of separation and capture technologies; and
- increasing education efforts to inform citizens about the use of fossil fuels combined with geologic carbon sequestration.

Advanced Nuclear Generation

The ability of nuclear power to play a significant role in reducing GHG emissions over the next half-century depends upon what happens in the next 10 to 15 years. The question is whether, in that time frame, the nuclear industry can overcome serious obstacles, including economic concerns, waste, and safety, and launch a major deployment of nuclear power plants. Near-term policy options identified through the 10-50 Workshop to address these barriers include:

- re-ordering of the priorities the U.S. Department of Energy (DOE) nuclear fuel cycle R&D to focus on the "once-through" fuel cycle;
- electricity production tax credits for "first mover" nuclear plants;
- significant expansion in size and scope of the U.S. DOE's nuclear waste management R&D;
- strengthening and reorienting of the current international non-proliferation regime; and
- public dialogue and education regarding the costs and benefits of nuclear power, especially in the context of climate change.

Renewables

Despite the significant potential for growth of renewables, these sources currently provide only a small fraction of commercial energy in the United States and around the world. Closing the gap between the current low level of renewables deployment and their high potential will require significant and sustained policies. Near-term policy options include:

- establishment of a national Renewable Portfolio Standard with set-asides for specific generation technologies and with tradable renewable energy credits;
- a major RD&D effort by the U.S. DOE focused on the use of renewables beyond niche markets;

- national test beds for new electricity grid systems that enable a broader set of power supply options, including intermittent and distributed energy and combined heat and power;
- increased research on expanding energy storage options;
- pollution fees for polluting energy sources; and
- continued support (e.g., through tax credits) to help renewables become competitive with fossil fuels for electricity generation.

Conclusions

Using a portfolio of energy technologies and policies, the United States can be well into a transition to a low-carbon future by 2050. However, achieving such a future necessitates a significant, explicit, and comprehensive commitment to climate-friendly policy and investment. In addition to economy-wide policies that establish a carbon price, technology-specific policies would stimulate further improvements in key technologies. An effective policy portfolio should work to both push and pull a wide variety of low-carbon energy technologies into the market. More, better-managed, and stable funding of RD&D is needed over the short, medium, and long term as well. Public and private leadership, consumer and citizen involvement, engagement of the research community, and international cooperation will also be key to such a transition. Most importantly, it is critical to start now on all fronts—policy and education, and research, demonstration, and deployment—to spur the investments necessary to provide for a low-carbon future both domestically and internationally by 2050.

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Proceedings Overview

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PEW CENTER ON Global CLIMATE CHANGE

NATIONAL COMMISSION ON ENERGY POLICY

The Challenge of a Low-Carbon Future

Addressing the challenge of global climate change will require a significant reduction in annual greenhouse gas (GHG) emissions in the United States and throughout the world by 2050. A commonly stated goal is to stabilize atmospheric concentration of carbon dioxide (CO_2) at twice its pre-industrial level.[1] To meet such a goal in the context of increasing global demand for energy, an increase of roughly 100 to 300 percent of present-day worldwide "primary power" consumption would need to come from non-CO_2-emitting sources such as renewables, nuclear, and the use of fossil fuels with carbon capture and sequestration.[2] In addition to low-carbon primary energy sources, a future low-carbon economy will require widespread use of lower-carbon fuels and energy carriers such as hydrogen, and significant improvements in the efficiencies of energy production, distribution, and end-use technologies.[3] The transition to a low-carbon economy could have other benefits, including increased energy security, improved public health, and increased economic development, but it will take several decades and will not be easy. Achieving this transition will require near-term and long-term actions. In the near term, it will be necessary to take advantage of current technologies and opportunities, and to make substantial investments in the technologies of the future.

It will be especially difficult to meet the technological challenges inherent in developing and deploying a suite of low-carbon energy technologies while achieving the traditional goals of U.S. energy policy (i.e., providing extensive energy services at low cost and through secure supply to a growing population and economy). Furthermore, low-carbon energy technologies that compete with entrenched conventional (and usually high-GHG-emitting) technologies are likely to encounter market, political, and societal barriers to deployment.

Accordingly, there is a clear need to initiate and sustain policies to push and pull low-carbon technologies into the market. Without such policies, businesses, consumers, and citizens are missing opportunities for cost-effective GHG reductions and investment for the future. Too often, the debate over GHG emission reductions pits near-term actions against long-term investments in technology, when both are necessary. A variety of policies, public and private leadership, and broad societal engagement will be needed to bring low-carbon technologies into the market. Characteristics of the energy sector—long capital cycles,[4] a high degree of system inertia, and susceptibility to path-dependency[5]—highlight the need to begin now to promote technological change and enable far-reaching deployment over the next 50 years.

Background on the "10-50 Solution"

Considering the long-term nature of the climate change challenge, the Pew Center on Global Climate Change and the National Commission on Energy Policy (NCEP) hosted a workshop entitled "The 10-50 Solution: Technologies and Policies for a Low-Carbon Future" in March 2004.[6] The overall goal was to articulate a long-term vision of the technologies and industrial process changes that would have to be in place 50 years from now to effectively address climate change, as well as the policies that would have to be initiated in the short, medium, and long term to achieve this vision. More specifically, the workshop aimed to achieve three goals:

- ☐ Analyze the strengths, weaknesses, barriers, and opportunities for technological options that could enable a low-carbon future;
- ☐ Develop plausible time frames for when various low-GHG technologies and strategies might start to generate significant GHG reductions; and
- ☐ Identify steps (particularly policies) that could facilitate the development and deployment of these technologies.

In preparation for the workshop, the Pew Center and NCEP commissioned new analyses in five key technology areas with the potential to play a significant role in a low-carbon economy: efficiency, hydrogen, carbon sequestration/coal gasification, advanced nuclear technologies, and renewables. This is not an exhaustive list of future low-carbon energy technologies. Although many other technologies and solutions such as the use of biofuels, terrestrial sequestration, and land use changes[7] will likely play a role in the transition to a low-carbon future, the workshop restricted its focus to only five of the critical low-carbon technology options due to resource constraints. In addition, lessons drawn from analyses of these technologies should inform policy-making that could promote other low-carbon energy technologies as well. One overview paper and two to four contributing pieces were commissioned in each of these technological areas to provide alternative views of the likely technological path forward in the short, medium, and long term; these papers also examined relevant challenges and policy considerations for each technology area. Overview authors were asked to present their papers as part of panel discussions at the workshop.

In addition to panels discussing the technologies identified above, the workshop featured several other panels and presentations. One panel explored opportunities in industry for reducing GHG emissions and policy options for encouraging further reductions. The role of natural gas in the transition to a low-carbon future was discussed through a brief presentation, and it was a topic of discussion throughout all of the workshop sessions. Finally, keynote speakers shared their perspectives on relevant topics including an update on the implementation of the United Kingdom's plan to reduce GHG emissions by 60 percent over the next 50 years,[8] opportunities for addressing climate change and energy security concerns simultaneously, and examples of how forward-thinking states and businesses are taking action on the issue of climate change and energy policy in the absence of federal leadership.

More than 100 policy-makers, business leaders, NGO representatives, and leading experts participated in the workshop.[9] Starting with the background papers and presentations, participants worked to identify options for promoting low-carbon energy technologies and industrial processes in the near, medium, and long term. Technological uncertainty, policy uncertainty, and uncertainty regarding the degree of success of policy-induced technological change prevented many participants from offering many policy recommendations beyond the near term. Thus, most workshop discussions focused on the policies needed within the next decade or two to enable these technologies to be widely deployed over the next 50 years and beyond. This overview summarizes the papers and identifies key points brought out in the conference.[10]

Status, Potential, and Options for Promoting Development of Five Low-Carbon Energy Sources and Technologies

A portfolio of new technologies and policies will be needed to enable the transition to a low-carbon future by 2050. Workshop participants voiced widespread support for a broad national policy that establishes a carbon price through market-based tools such as cap-and-trade or taxes. Revenues from such measures could be used, in part, to support research, development and deployment (RD&D)—another key component of a comprehensive program to achieve significant emission reductions. Various policy approaches to stimulating specific technologies as well as economy-wide reductions are discussed below.

In the pull-out at the front of this proceedings, Figure 1 summarizes the technological status and expected deployment of the five areas of focus in the 10-50 Workshop. This figure shows the significant potential to reduce energy-related GHG emissions by 2050 through a portfolio of technology options. However, many of the assessments and predictions of technological potential shown here are based on the assumption that policies enacted in the near term would enable increased development and mid- and long-term market deployment of the indicated technologies.

The pull-out at the back of this proceedings, Figure 2, describes various policy proposals put forth by workshop participants. A mix of these policies, plus others yet to be defined, will probably be necessary to enable the development and deployment over time of the technologies described in Figure 1. As Figure 2 indicates, numerous policy proposals suggested in workshop papers and discussions focused on the next 10 to 15 years, and very few aimed beyond the 2015–2020 time frame. This more limited focus can be attributed partly to a hesitancy to make policy prescriptions in the face of technological (and other) uncertainties, but it also reflects the widespread sentiment of the 10-50 Workshop participants: that it is imperative to start now to develop technologies that will enable a low-carbon economy by 2050.

Whereas Figure 2 emphasizes the need for near-term policy actions, Figure 1 shows the significant and continued potential to reduce GHG emissions by deploying these low-carbon technologies throughout the next five decades.[11] The integration of Figures 1 and 2 shows that a suite of policies must be enacted in the near term to enable continuous incremental reductions in GHG emissions through deployment of these technologies and to better position society to select among low-carbon options in the future.

Figures 1 and 2 also show that enabling a low-carbon future will likely entail the utilization of a variety of low-carbon technologies and policies, and that both broad and technology-specific policies will be required. Below is a discussion of the current and future technological potential of each of the five areas studied, as well as policies to create incentives for deployment of each of these technologies over the long term.

Energy Efficiency

Broadly speaking, energy efficiency has saved the U.S. economy billions of dollars in energy expenditures since the middle of the 20th century. Energy consumption per dollar of real GDP has fallen by more than 50 percent since 1949,[12] and energy price changes as well as specific policies—including corporate average fuel economy (CAFE) standards,[13] mandated appliance energy efficiency standards, and building codes—have resulted in billions of dollars of savings from reduced energy imports and electric energy expenditures, as well as hundreds of millions of tons of CO_2 emission reductions.

The technological potential for energy efficiency improvements in the next 10 to 20 years, and potentially throughout the next 50 years, remains large. However, the degree to which these potential savings are realized will depend on increases in the cost of energy, adoption of policies, public and private investments spurred by incentives and pricing, as well as continued improvements in energy-efficient technologies. Nonetheless, even with present-day technologies, the potential energy savings and CO_2 emissions reductions from energy efficiency are significant and critical. A few examples illustrate this point:

- Adoption of four pending appliance standards (clothes washers, fluorescent light ballasts, water heaters, and central air conditioners) could result in significant energy savings for U.S. consumers, possibly saving as much as $10 billion in energy costs by 2010[14]
- Replacement of four building technologies (ballasts, lamps, windows, and refrigerators/freezers) with high-performance alternatives during the natural building stock replacement cycle could save 190 billion kilowatt hours (kWh) by 2010 and an additional 130 billion kWh by 2050[15]
- Creation of "cool communities"—which entails using more reflective roofing materials and better use of landscaping for solar absorption and shading—could reduce annual cooling loads by 10 percent and thereby reduce total U.S. annual energy use by 0.5 percent[16]
- Widespread adoption of "daylighting"[17] technologies in U.S. buildings could reduce 3–6 percent of total U.S. energy use (or 30–60 percent of lighting-related energy)[18]
- Widespread adoption of better air conditioning technologies compatible with natural ventilation and night or high mass cooling[19] could reduce total U.S. energy consumption by 5 percent[20]

- Use of distributed wind, solar, and geothermal resources located on site of many buildings in the United States by 2050 could make them net energy exporters[21]

The technological opportunity in the industrial and transportation sectors is also large. Estimates of the long-term potential for energy-efficiency increases in the industrial sector range from 30 to 65 percent,[22] and fuel economy of automobiles and light trucks could increase by 50 to 100 percent by 2030.[23]

Policy Options

Some near-term policy options are likely to increase adoption of energy-efficient technologies:

- Mandatory reporting of GHG emissions. As seen with reporting of the Toxics Release Inventory[24] and individual firm GHG targets, entities conducting inventories find opportunities for cost-effective efficiency improvements and other GHG emission reductions[25]
- Adoption and promotion of building codes focused on maximizing GHG reductions—examples might include "cool" roofs, daylighting, and ventilation
- Federal mandatory appliance standards—attractive candidates include air conditioners, clothes washers, fluorescent light ballasts, and water heaters
- Increases in public RD&D in innovative energy efficiency technologies and integrated systems, including publicly funded demonstration programs that recognize major building type and climate specific opportunities
- Increased CAFE standards
- Incentives for the private and public procurement of highly efficient technologies in areas from buildings to vehicles such as hybrid-electric and advanced diesel vehicles

Hydrogen in Transportation

If produced from low- or zero-carbon energy sources, hydrogen can be used as a transport fuel with nearly zero "well-to-wheels"[26] GHG emissions.[27] Hydrogen also has the potential to achieve other societal benefits such as reduced local air pollution and increased energy security. Presently, hydrogen is predominantly produced for use in the worldwide petrochemical industry, and its use in transportation applications is insignificant.[28] Continued R&D on hydrogen technologies is likely to continue for the next 10 to 15 years, with limited fleet and demonstration-project testing. Many analysts think that a societal decision on hydrogen's long-term viability as an energy carrier will be needed in the 2015–2020 time frame. Assuming technological and cost progress, hydrogen vehicles could start significantly penetrating the market after 2025.[29]

Significant technical challenges face the widespread use of hydrogen as a transportation fuel, including difficulties associated with on-board hydrogen storage and the durability and cost of hydrogen conversion devices (specifically fuel cells). In addition to overcoming these many technical challenges, a reduction in economy-wide GHG emissions from the use of hydrogen as a transportation fuel depends on the cost and technical feasibility of producing hydrogen from low-carbon energy sources, including renewables and fossil fuels with carbon sequestration. Despite these significant challenges, hydrogen offers perhaps the best hope for solving multiple societal challenges facing current and future transportation energy use, and thus it deserves serious consideration.[30] However, the political will to address the external impacts of energy use through policy and technological progress will determine whether hydrogen plays a major role as a future energy carrier.[31]

In light of the challenges facing the use of hydrogen as an energy carrier, it is important to continue to explore other options for reducing GHG emissions from the transportation sector, including biofuels and, most importantly, highly efficient vehicles such as hybrid-electric vehicles. In addition to offering the potential for significant near- and medium-term GHG reductions, continued commercial experience with many technologies used in hybrids (e.g., electric drive trains, advanced batteries, and sophisticated electronic control systems) will be beneficial for any eventual hydrogen internal combustion engines or fuel cell vehicles. In addition, policies that promote the use of highly efficient vehicles are likely to also encourage the use of hydrogen vehicles.

Policy Options

The near-term policy options listed below will be needed to enable hydrogen to make a significant contribution to a low-carbon economy by 2050:

- Development of a national energy policy that addresses the external costs of energy use, including security, climate change, and traditional air pollutants
- Continued and increased federal support for hydrogen-related R&D, including special emphasis on low-carbon hydrogen production, hydrogen storage, and fuel cells
- National and international harmonization of hydrogen codes and standards
- Continued federal and state government support for, and participation in, public/private partnerships and demonstration programs (e.g., California Fuel Cell Partnership, FreedomCAR, and international cooperative efforts)
- Incentives to increase the development and deployment of hybrid technology and vehicles and other low-carbon transportation technologies—many of which are part of an evolutionary path toward the use of hydrogen and fuel cells
- Education of consumers and the public regarding the societal costs of transportation energy use and options for reducing such impacts, specifically including hydrogen

Carbon Sequestration/Coal Gasification

The use of coal gasification technologies coupled with carbon capture and sequestration in geologic formations has the potential to allow the United States (and the world) to use its significant coal resources without releasing substantial GHG emissions to the atmosphere. Although coal is mostly used for electricity generation, it is also possible to make hydrogen from coal using gasification technologies. Thus, production of electricity and hydrogen from coal, combined with carbon capture and sequestration (CCS), could enable significant CO_2 emission reductions from both the electricity and transportation sectors, which currently account for more than two-thirds of U.S. GHG emissions.

Injection of CO_2 into geological formations has been practiced for decades in the United States in “enhanced oil recovery” (EOR) projects in oil and gas wells.[32] In addition to EOR projects, there are six CCS projects underway worldwide. However, none of the six currently operating projects nor any other planned projects sequester as much CO_2 per year as would be needed to offset emissions from an average U.S. coal plant.[33]

Although estimates of total carbon storage capacity vary widely, the global geologic capacity of depleted oil and gas reserves, coalbed methane reserves, and salt-water filled formations is significant—most likely enough to enable sequestration of significant percentages of global GHG emissions from the use of fossil fuels. One estimate of the “known” resource places U.S. storage capacity at about 50 years’ worth of CO_2 emissions from U.S. electric power plants in depleted oil and gas reserves alone.[34] Further work is needed to determine the capacity of salt-water filled formations that are suitable for carbon storage (potentially the largest resource for carbon sequestration).

Despite the potentially large storage capacity, significant barriers remain before widespread use of coal gasification with CCS would be feasible, including

- validation of the geologic integrity of storage;
- cost of the carbon capture and separation technologies;
- integration of gasification, CCS, and electricity generation technologies; and
- public acceptance of geologic storage of CO_2.

Policy Options

If these issues are properly addressed within the next decade, coal gasification with CCS could enter the commercial market around 2020–2025. Many experts conclude that conducting a mix of domestic and international public/private partnership demonstration projects is the best way to overcome some of these barriers. Accordingly, the main policy recommendation regarding CCS is a significantly ramped up demonstration and validation program for CCS technology and the integrity of geologic storage, starting immediately. These recommendations, as well as other near-term policy options are identified below:

- International coordination to plan, fund, and deploy coal gasification with CCS trial projects that focus on remaining technical issues and with publicly shared results (e.g., adequately addressing remaining uncertainties will likely require four to six projects, at an estimated cost of approximately $5 billion, and an estimated project lifetime of 10 years)
- Establishment of carbon sequestration trial projects in the United States to validate the integrity of geologic storage (e.g., such validation will likely require four such projects at an estimated cost of approximately $1 billion, and an estimated project lifetime of 10 years)
- Removal of policy disincentives to shutting down old coal plants
- Initial establishment of a regulatory framework for underground CO_2 storage
- Promotion of R&D to reduce the cost of separation and capture technologies
- Increase in consumer and citizen education efforts regarding the scientific and social costs and benefits of continued use of fossil fuels with geologic carbon sequestration

Advanced Nuclear Generation

Nuclear power currently provides approximately 20 percent of U.S. electricity supply from 104 operating reactors. Conventional nuclear power is considered by most to be a "mature" technology. Despite its significant role in the U.S. electricity mix, the last new nuclear plant was ordered in 1979,[35] and there are no current plans to build more in the United States.[36] Furthermore, approximately 10 percent of U.S. nuclear plant licenses will expire at the end of 2010, and more than 40 percent will expire by 2015.[37] Any significant ramp-up of nuclear capacity would likely be a lengthy process, due in large part to the significant time required to license and build a new nuclear plant. Thus, the ability of nuclear power to contribute to avoiding significant GHG emissions by 2050 will likely be determined by whether a major deployment of nuclear power in the United States starts in the next 10 to 15 years.

Such a deployment highly depends on the degree to which the nuclear industry can overcome serious barriers, including

- cost;
- technical, political, and social concerns about nuclear waste disposal;
- increased proliferation risk; and
- public concern about the continued and expanded use of nuclear power.[38]

Policy Options

Listed below are some of the near-term policy options that could address the barriers to nuclear generation and that could increase the likelihood of a large-scale deployment scenario. However, even with the adoption of a comprehensive suite of policies to promote nuclear power, the role of nuclear power in the future will ultimately be determined by the willingness and ability of the electric industry to increase deployment of nuclear plants.

- Electricity production tax credits for "first mover" nuclear plants up to 10 gigawatts electric (Gwe) at a level similar to the wind production tax credit (currently 1.8 cents/kWh)
- Significant expansion in size and scope of the U.S. DOE's nuclear waste management R&D
- Strengthening and reorientation of the current international safeguards regime to meet the non-proliferation challenges of globally expanded nuclear power
- Re-ordering of the priorities of the U.S. DOE nuclear fuel cycle R&D to focus on the "once-through"[39] fuel cycle
- Public dialogue and education on the costs and benefits of nuclear power, especially in the context of climate change

Renewables

Some experts estimate that renewable sources of energy, including wind, solar, geothermal, oceans, and biomass, could provide between 20 and 50 percent of U.S. electricity by 2050.[40] Despite this potential for growth, these sources currently provide a small fraction of commercial energy in the United States and around the world. For instance, in 2000, wind, solar, and geothermal energy (in combination with combustible renewables, and the burning of garbage and other wastes) collectively provided just 1.6 percent of electricity production worldwide.[41] In 2002, these sources provided 2.2 percent of electricity generation in the United States.[42]

Despite their low levels of deployment relative to other electricity-generating technologies, renewables such as wind and solar continue to sustain impressive annual growth rates. The wind industry grew by 30 percent annually worldwide over the past five years, and annual global growth in the production of photovoltaic cells holds steady at roughly 20 percent.[43] Nevertheless, closing the gap between the current low level of renewables deployment and their high potential will likely require significant and sustained policies and programs.[44]

Policy Options

Listed below are policy options to motivate and support a massive ramp-up of renewables. Each of these policy proposals focuses on one or more of the commonly cited market or technical barriers facing widespread deployment of renewables: cost, intermittency,[45] the remote nature of many renewable resources,[46] and the number of generation sources that would be required.[47]

- A national renewable portfolio standard with set-asides for specific generation technologies[48] and with tradable renewable energy credits

- A massive “third stream”[49] of R&D by the U.S. DOE focused on renewables; such a program should be on the order of an “Apollo” project and should include three characteristics:
    - A focus (at the National Renewable Energy Laboratory and other national labs) on making renewables commercially competitive beyond niche markets
    - Reduced uncertainty in funding for renewables—possibly “forward-funding”[50] of renewables R&D to reduce the year-to-year variability of the annual appropriations process
    - Revamping of the U.S. DOE’s renewables R&D portfolio to include more high-risk R&D (i.e., away from strictly risk-averse R&D portfolios)
- National test beds for new electricity grid systems followed by an extensive modernization of the grid, including intermittent and distributed energy and combined heat and power
- Increased research on expanding energy storage options
- Pollution fees for polluting energy sources
- Continued support to help renewables become competitive with fossil fuels for electricity generation (e.g., through tax credits)

Common Themes and Policy Recommendations

In addition to the technology-specific insights above, a number of common themes and policy recommendations emerged from the workshop. Broadly speaking, these can be grouped into four over-arching points: (1) clear and consistent policy signals are urgently needed; (2) a portfolio of technologies and policies will be needed to drive the absolute reduction of GHG emissions necessary to address climate change; (3) a low-carbon technology revolution will require both leadership and broad engagement throughout society; and (4) it is essential to start now. These common themes and policy recommendations are explained in more detail below.

Clear and Consistent Policy Signals Are Urgently Needed

Policy is needed to set the framework for a low-carbon future, and businesses and markets need to believe in the legitimacy of the policy framework. For instance, the United Kingdom is implementing a goal of reducing GHG emissions by 60 percent by 2050. Such a commitment sends a very powerful signal to markets that the UK government is serious about addressing climate change, and it helps to reduce the level of uncertainty in the investment decision-making process of private and public entities. It also aligns the government’s various efforts toward the same goal of reducing GHG emissions through advancing the RD&D agenda, transportation policy, energy policy, environmental policy, and other areas. In addition, the UK government’s willingness to revise policies after input from businesses (specifically establishing an interim target for the year 2015 as part of its “renewables obligation”) can be key to establishing legitimacy and to further strengthening market confidence.[51]

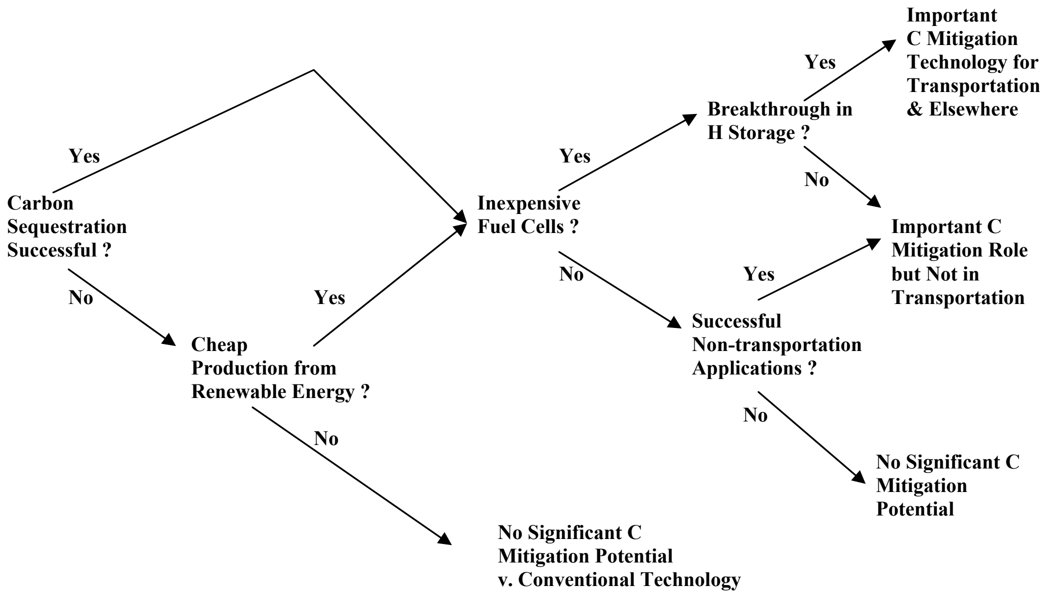
Additional policies that send clear economy-wide signals of a shift towards a low-carbon future include mandatory reporting of GHG emissions, and imposing a price on GHG emissions such as would be established through enacting an emission cap-and-trade system. However, such "signal" policies should be supplemented where appropriate with technology-specific policies as well as policies that broadly promote the significant development and deployment of low-carbon energy technologies. The UK plan includes such necessary supportive policies. It is particularly important to implement climate policies now, because the current policy uncertainty is costly for firms that must make investment decisions without a clear idea of what future climate policies will govern them. For example, the long lifetime of capital stock that firms invest in today may slow the rate at which the United States can obtain significant GHG emission reductions in the future.[52]

> **Mandatory Reporting of GHG Emissions.** Past experience shows that emission tracking and reporting by companies can be extremely effective at motivating GHG reductions and innovation—companies find that "what gets measured gets managed." One important first step in any domestic program could be developing a reliable and credible system for tracking and reporting GHG emissions. Similar to the federal Toxics Release Inventory (TRI) program, a mandatory GHG reporting program would apply to all major sources of GHG emissions and would require disclosure of the reports in a publicly accessible Internet-based database. Between 1989 and 1999, manufacturers' release of 340 chemicals covered under the TRI program dropped by 45.5 percent.[53]
>
> **GHG cap-and-trade.** Emission trading has emerged as a popular and cost-effective policy tool for controlling air pollution, perhaps most notably in the reduction of sulfur dioxide (SO_2) emissions under the U.S. Acid Rain program. A properly designed program provides a framework to meet emission reduction goals at the lowest possible cost. It does so by giving emission sources the flexibility to find and apply the lowest-cost methods for reducing pollution. Emission trading is especially well suited for controlling GHG emissions because the effects of GHGs are the same regardless of where the source is located and when the emissions occur.[54] A conventional cap-and-trade program establishes an economy-wide or sectoral cap on emissions (in terms of tons per year or other compliance period) and allocates or auctions tradable allowances (the right to emit a ton of GHGs) to GHG emission sources or fuel distributors. The total number of allowances is equal to the cap.[55]

Policy Flexibility Should be Balanced With Reasonable Policy Certainty

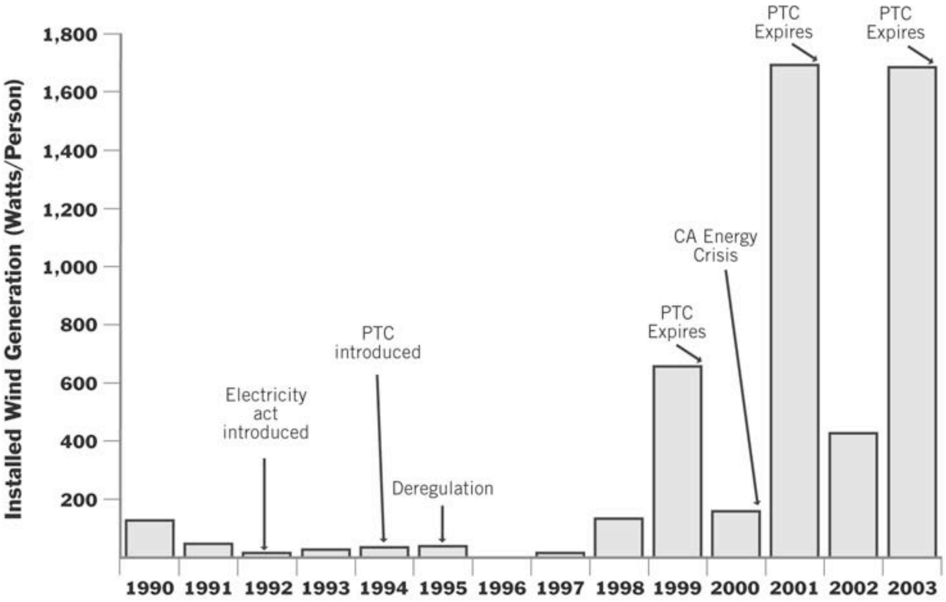
Early policies should not be too prescriptive in picking one technology while significant technological and market uncertainty remains. On the other hand, uncertainty regarding future technology options cannot be used as an excuse for near-term inaction. Developing an effective strategy for addressing the low-carbon energy challenge will require ongoing evaluation and course corrections as technologies evolve. Therefore, policies need to be structured to ensure the flexibility to allow them to take advantage of near-term options, while keeping the door open to other long-term options. Mistakes will be made, and precautions must be taken to reduce their frequency and magnitude, but the likelihood of mistakes happening should not stop aggressive experimentation with new technologies and policies. The challenge of designing policies under technological uncertainty and the possible need for societal choices at some point in the future are highlighted in Figure 3.[56] This chart shows many of the potential technology breakthroughs involved in a transition to hydrogen over the next few decades, and it highlights the need for policy flexibility.

Figure 3: "Decision Analysis" of Hydrogen Energy as a Carbon Dioxide Mitigation Strategy for Transportation



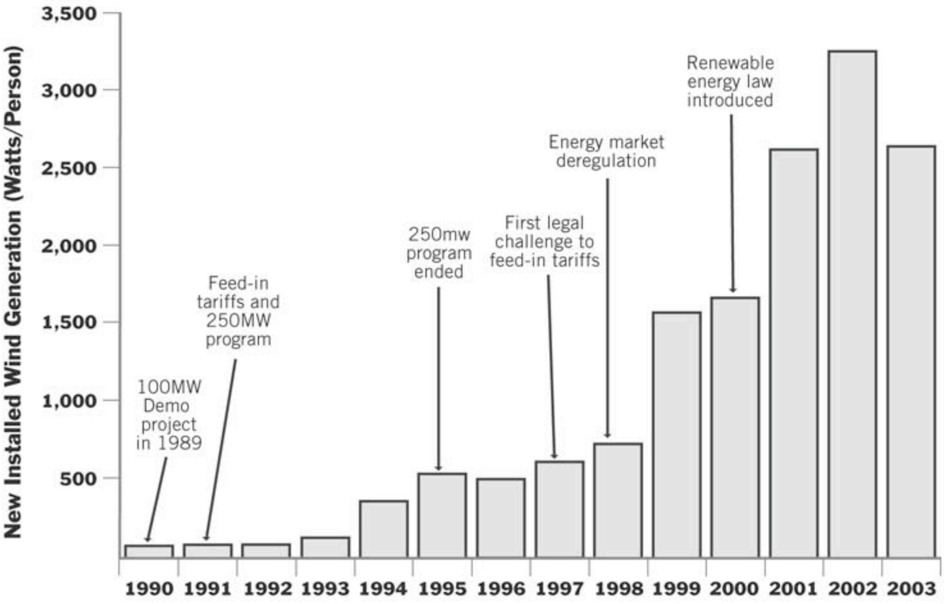
At the same time, any suite of policies must balance the need to allow for iterative policy development with the need for policy certainty over a reasonable time period to foster sustained research and market development. The effect of inconsistent policy support for low-carbon energy technologies is graphically demonstrated in Figures 4 and 5. Figure 4 shows the "boom and bust" effect of the existence and expiration of the wind production tax credit (PTC) in the United States, while Figure 5 depicts the steady wind industry growth in Germany given steady regulatory support.

Figure 4: The effect on the U.S. wind industry of the expiration of the PTC[57]



Source: BTM Consult ApS and Vestas Wind Systems

Figure 5: The effect of consistent policy support for wind in Germany[58]



Source: BTM Consult ApS and Vestas Wind Systems

The figures demonstrate that policies to promote low-carbon technologies must be in place long enough to foster market confidence and sustain market growth over a reasonable period of time.

A Portfolio of Technologies and Policies Will Be Needed to Address Climate Change

There was general consensus that no single technology or policy will be sufficient to enable a low-carbon future by 2050. Many low-carbon energy technologies and fuels are currently available or offer great promise for the future (including many not addressed in the workshop), and such a portfolio will be needed to satisfy the world's current and future energy needs in a climate-friendly manner. Similarly, a suite of policy options will likely be needed to push and pull these technologies into the market. Although many past governmental attempts to "pick winners" have been unsuccessful, a comprehensive strategy to enable a low-carbon future will likely require the development and enactment of both general and technology-specific policies, because, over time, investment will likely center on specific viable low-carbon technologies. The government will likely have to engage in some form of technology husbandry with its limited R&D resources. For example, if hydrogen is to become a significant transportation fuel, development of hydrogen infrastructure must begin at some point—a process that is unlikely to occur in the absence of specific policies. The challenge is to design policies that are neutral enough to promote the development and deployment of a suite of low-carbon technologies, yet also tailored enough to push and pull some specific low-carbon technologies that might not enter the market under a broad policy mechanism. Both types of policies are needed.

Efficiency Will be Key in Both the Near and Long Term

Efficiency will be key to achieving a low-carbon future in 2050. For example, the United Kingdom expects efficiency gains to account for nearly half of its targeted 60 percent CO_2 reductions over the next 50 years,[59] and in 1997, the U.S. President's Council of Advisers on Science and Technology (PCAST) found that cumulative efficiency gains of 2 percent per year (in terms of energy use per GDP) could reduce the need for low-carbon energy sources by two-thirds by 2050.[60] There are also many opportunities for significant efficiency gains in the near term, especially in the building and transportation sectors, but some degree of regulation and/or standards will probably be necessary to realize these gains in the market.

> **Buildings are a big variable over the next 50 years.** The potential for significant reductions in building energy use over the next 50 years is huge, yet the degree to which this potential will be realized remains uncertain. New and enhanced policies and initiatives will likely be needed to realize the potential for GHG reductions from the building sector, possibly including enhanced use of building codes and standards (e.g., LEED – Leadership in Energy and

Environmental Design standards[61]). U.S. DOE-sponsored design competitions might help to inform buildings codes and standards development. Increased product standards (e.g., appliance efficiency standards) also could facilitate emission reductions.

Hybrids are also key to a "10-50" strategy. The increased use of hybrid vehicles may enable significant GHG emission reductions in the near, medium, and possibly long term. Encouraging the deployment of hybrids, or other lower-GHG vehicles such as advanced diesels or cars powered by biofuels, is consistent and complementary with policies that may promote a transition to a hydrogen-based transportation system. Increased "hybridization" and/or "electrification" of the drive train is likely to be critical to future hydrogen-based vehicles that may be deployed in significant numbers (most likely after around 2030), and hybridization will likely be key to any future options for light duty vehicles.[62]

Natural Gas Could Play a Key Role in the Transition

Natural gas will play an important role in any transition to a low-carbon future, but the extent of this role will be determined by the degree of success of efforts to address supply and price concerns in the United States and the global market. During the 1990s, natural gas emerged as the fuel of choice for new electricity-generating capacity in the United States because prices were low, new gas plants are relatively quicker and cheaper to build, and natural gas is cleaner than other fossil fuels. For example, until cost-effective CCS technologies are developed and employed, combustion of one Btu of natural gas will produce 40 percent less CO_2 than combustion of one Btu of coal.[63]

Recently, however, U.S. natural gas prices have increased dramatically, depletion rates of domestic conventional natural gas resources have risen rapidly, and many known reserves are in areas that are restricted or that tend to be difficult and expensive to produce.[64] As a result, several energy companies have announced plans to build new coal-fired units, and the United States has seen significant natural gas demand destruction,[65] particularly in natural-gas intensive industries such as fertilizer manufacturing. Nonetheless, aggregate demand for natural gas in the United States is expected to increase from 22.8 trillion cubic feet (TCF) in 2002 to 31.4 TCF by 2025.[66] A combination of efficiency improvements to reduce demand and measures to increase supply will be necessary for natural gas to facilitate the transition to a low-carbon future. A suite of technologies and investments will be needed to address the following key natural gas challenges:

- More efficient use of natural gas resources (this is particularly critical for taking pressure off supply in the near term);
- Support for research and development of conventional and unconventional gas resources;
- Addressing of domestic supply constraints (e.g., development of new reserves, siting of liquefied natural gas (LNG) terminals);
- Access to stranded gas resources; and
- Extension of the resource base through alternative fuels.[67]

Increased and Revamped RD&D is Necessary

Effective research, innovation, development, and deployment strategies will be critical to enabling a low-carbon energy future. Current levels of federal RD&D need to be significantly increased to reflect parity with other sectors in the U.S. economy (on an RD&D dollars spent per GDP-generated basis) and with the magnitude of the challenge of enabling a low-carbon energy future. Equally as important, strategies for managing these funds need to be revamped. Current RD&D efforts on low-carbon technologies suffer from a cultural focus on niche markets, inter- and intra-agency "stove-piping," uncertainty caused by the annual appropriations process and cycle, and detrimental Congressional earmarks on scarce funds. The federal government needs a more integrated approach to RD&D—to focus the appropriate agencies and resources on critical RD&D needs at appropriate times within a long-term R&D framework. "DARPA-like"[68] management is needed to instill a culture focused on development and commercialization of these technologies, and forward funding would help reduce the level of uncertainty and detrimental earmarks. Public/private partnerships and government procurement have a key role to play as developers and incubators of technology and to foster "learning by doing"—a critical step in bringing down the cost of low-carbon technologies and increasing deployment. While support for breakthrough technologies is often appealing, experts point out that what often appears to be a breakthrough is indeed the result of years of incremental investment and work. Public/private partnerships are an effective vehicle for enabling sustained incremental improvements in the performance and cost of low-carbon technologies.

International Efforts are Needed

Domestic RD&D and policy efforts need to be conducted in concert with international efforts, while considering the energy needs of the international community. Some RD&D efforts (e.g., those focused on coal gasification/carbon sequestration) would benefit greatly from collaboration and/or coordination with those in other countries. International efforts are needed to harmonize codes and standards for lower-emission vehicles, especially those relating to hydrogen vehicles and infrastructure.[69] Basic energy-service needs and desires will dominate the energy development trajectories of much of the developing world over the next 50 years. RD&D efforts between developed and developing countries, although sometimes politically unpopular, can be mutually beneficial, and they will be necessary to enable a worldwide low-carbon energy future in 2050.

A Low-Carbon Technology Revolution Will Require Both Leadership and Broad Engagement Throughout Society

The Need for Leadership

Enabling a low-carbon future will require strong leadership from public- and private-sector decision-makers including federal and state lawmakers, business executives, and other public leaders. Like sending a "signal" to a market through a cap-and-trade program, high-profile leaders' acknowledgement of the collective need to address climate change can profoundly affect the behavior of consumers, investors, employees, and citizens. Such impacts have been demonstrated when CEOs of large corporations have made reducing GHG emissions within company operations a high priority. Experience has shown that when employees are told to look for opportunities to reduce GHG emissions they have done so very effectively. Such leadership is also being demonstrated by many state governors who have recognized the need to address the significant risks that climate change poses to their states, and who have decided to fill the leadership void left by the federal government.

The Need for "Bundling," Non-traditional Alliances, and Public/Private Partnerships

Many workshop participants stressed that effective use of "bundling," alliances, and public/private partnerships will be necessary to enable a low-carbon future. Policy initiatives that promote low-carbon energy technologies will be most effective if they are bundled with efforts that address multiple societal concerns such as increasing energy and national security, reducing conventional air pollution, and promoting local economic development. Enactment of such bundled policies may benefit from alliances of stakeholder groups that have not traditionally worked together, including national security experts and environmentalists, and proponents of nuclear power and proponents of renewables. Similarly, bundling of individual GHG reduction measures will also be important to increasing the deployment of low-carbon technologies. For example, maximizing the deployment of multiple small building efficiency measures may be best achieved through building codes or similar policy tools, and the deployment of renewables could be significantly increased through cost reductions enabled by bundling renewables projects with efficiency measures. Finally, public/private partnerships will be important in accelerating the development and deployment of low-carbon technologies. Such collaborations draw on the specific expertise of government, business, and academia, combining scarce resources and sharing insights for effective research, development, and deployment outcomes.

The Role of Consumers and Citizens

The need to involve consumers and citizens in the development of markets for low-carbon energy technologies and fuels is obvious to many, but strategies for doing so are not as readily apparent. Public education is needed to explain the benefits of addressing climate change, the risks of inaction, and the options for reducing GHG emissions. Better labeling of fuels (e.g., at the pump) and energy-consuming products (e.g., appliance energy-use labels), and increased availability of relevant information on energy generation and use could be effective in raising consumer awareness. Product standards and increased availability of “green” power also would affect the markets for low-carbon technologies. In addition, increased consumer information in the building and electricity sectors might play an important role (e.g., required disclosure of building energy use during sales transactions of the existing residential capital stock, and disclosure of sources and emissions to electricity consumers). Furthermore, policies that address mixed incentives (e.g., between landlords and tenants) may help to increase consumer interest in reducing energy use.

The Need for Greater Engagement from the Research Community

The financial resources and creative ingenuity of universities and private-sector research institutions need to be more focused on the critical challenge of providing for a future low-carbon energy system. Such increased engagement would likely include better funding for relevant graduate-level research, more attention to these issues in undergraduate and graduate education, and an institutional and collective focus on addressing the critical research issues related to low-carbon energy sources and technologies throughout the public and private research communities.

It Is Essential to Start Now

Finally, a recurring theme of the workshop was the need to immediately start developing technologies and policies to address climate change. Already some governments and businesses have begun taking steps to reduce emissions, but as the workshop papers make clear, more can and should be done in the near term. While climate change is a long-term problem and some solutions might take years to play out, many actions can be taken now to reduce emissions and to lay the groundwork for future technological development and associated GHG reductions.

Conclusions

Using a portfolio of energy technologies and policies, the United States can be well into a transition to a low-carbon future by 2050. However, achieving such a future necessitates a significant, explicit, and comprehensive effort, including policy signals to markets that indicate a long-term policy commitment to such a future. Clear GHG reduction targets for both the near and long term are needed to encourage consumers, citizens, and companies to look for ways to reduce GHG gas emissions; to spur private investment in low-carbon technologies; and to set the broader framework for policies that will enable a long-term GHG reduction target to be realized.

However, such economy-wide signals, although necessary, will not be sufficient to enable a low-carbon energy future. Significantly reducing energy-related GHG emissions by 2050 will require continued improvements in energy-related technologies, and it will require policies that push and pull a wide variety of low-carbon energy technologies into the market. To that end, increased and refocused RD&D covering a broad suite of critical low-carbon energy technologies is needed, including a restructuring of RD&D portfolios to reflect the need for massive deployment of low-carbon energy technologies. Meaningful technology deployment will also require investments in critical energy-related infrastructure and robust market development policies. Dissemination of such technologies will also benefit from policies such as new efficiency standards and consumer labeling. In addition, public and private leadership, consumer and citizen involvement, engagement of the research community, and international cooperation will be key to developing and significantly deploying a suite of low-carbon technologies.

Analogous to an energy RD&D portfolio, the United States needs a flexible and evolutionary policy portfolio that consists of sound climate policies to promote GHG reductions, creates and promotes the use of new low-carbon technologies and fuels, and ultimately provides for the decoupling of economic growth and CO_2 emissions. Most importantly, it is critical to start now to spur the critical investments necessary to provide for a low-carbon future by 2050.

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[1] 550 parts per million (ppm) or less.

[2] Global primary energy consumption is currently approximately 12 terawatts (TW). See Hoffert, Martin I. 2004. Renewable Energy Options—An Overview. Paper prepared for the Pew/NCEP "10-50 Solution" Workshop. Washington, D.C., March 25–26, 2004; and Hoffert, M.I., K. Caldeira, G. Benford, et al. 2002. Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet. *Science* 298: 981–987.

[3] Although the largest potential for reducing GHG emissions lies in the reduction of CO_2 associated with fossil-fuel energy production and consumption, carbon sequestration and the reduction of non-CO_2 GHGs also offer opportunities for reducing GHG concentrations in the atmosphere. See Reilly, J.M., H.D. Jacoby, and R.G. Prinn. 2003. *Multi-gas Contributors to Global Climate Change: Climate Impacts and Mitigation Costs of Non-CO_2 Gases.* Pew Center on Global Climate Change, Arlington, VA.

[4] See Lempert, Robert J., Steven W. Popper, Susan A. Resetar, and Stuart L. Hart. 2002. *Capital Cycles and the Timing of Climate Change Policy,* Pew Center on Global Climate Change, Arlington, VA. See also Mintzer, Irving M., J. Amber Leonard, and Peter Schwarz. 2003. *U.S. Energy Scenarios for the 21st Century.* Pew Center on Global Climate Change, Arlington, VA.

[5] Path dependency refers to the concept that technological change and development are strongly influenced by past changes and choices.

[6] The 10-50 Solution: Technologies and Policies for a Low-Carbon Future, a workshop co-sponsored by the Pew Center on Global Climate Change and National Commission on Energy Policy (NCEP), Washington, D.C., March 25–26, 2004.

[7] Other important components of a GHG-friendly energy future that were not explicitly examined during the workshop may include coalbed methane, geothermal energy, nanotechnology, ocean wave energy, information technologies, sensors, materials, and biotechnology.

[8] See Department of Trade and Industry. 2003. *Energy White Paper: Our energy future—creating a low carbon economy.* The Stationary Office, London, UK (February). See http://www.dti.gov.uk/energy/whitepaper/index.shtml.

[9] A complete list of workshop attendees is available at the front of this proceedings.

[10] This overview by the staffs of the Pew Center and NCEP aims to summarize the main points and common themes from the workshop papers and the discussions at the workshop. It may not represent the

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views of all the authors of 10-50 Workshop background papers or of all of the 10-50 Workshop participants.

[11] That is, the boxes indicating significant GHG emissions reduction potential are more spread out along the timeline and are not as concentrated in the 2005–2015 time frame or the 2045–2055 time frame.

[12] Metcalf, Gilbert E. 2004. Energy Efficiency Overview Paper. Paper prepared for the Pew/NCEP "10-50 Solution" Workshop. Washington, D.C., March 25–26, 2004.

[13] CAFE standards were established in 1975 by Congress. They required new passenger car fuel economy to increase from 18.0 mpg in 1978 to 27.5 mpg in 1985, where the standard remains to this day. Congress also required NHTSA to set standards for light trucks, and the standards were recently raised to 22.2 mpg by 2008. See Greene, David L., and Andreas Schafer. 2003. *Reducing Greenhouse Gas Emissions from U.S. Transportation.* Pew Center on Global Climate Change, Arlington, VA.

[14] Loftness, Vivian. 2004. Improving Building Energy Efficiency in the U.S: Technologies and Policies for 2010 to 2050. Paper prepared for the Pew/NCEP "10-50 Solution" workshop. Washington, D.C., March 25–26, 2004, p. 2.

[15] Ibid.

[16] 6 percent of all U.S. energy is used in cooling residential and commercial buildings. Loftness, 2004, p. 2.

[17] Daylighing is the use of natural light to supplement or replace interior artificial lighting. See http://www.nrel.gov/clean_energy/passivesolar.html.

[18] 10 percent of all U.S. energy is used for lighting buildings. Loftness projects that adoption of daylighting technologies could reduce annual lighting energy consumption 30–60 percent. Loftness, 2004, p. 2.

[19] High-mass cooling utilizes material that aborbs heat or coolness and stores it for a long time (e.g. concrete) to keep a structure cool by extracting heat from indoor air during the day and releasing it at night. See http://hem.dis.anl.gov/eehem/99/990515.html#99051504.

[20] Loftness, 2004, pp. 2–3, based on the "effective use of natural conditioning with well-designed windows, window controls, and mechanical and lighting system interfaces, promises to yield major energy efficiency gains of up to 5 percent of all U.S. energy use."

[21] Loftness, 2004, p. 3.

[22] Price, Lynn, and Ernst Worrell. 2004. Improving Industrial Energy Efficiency in the U.S.: Technologies and Policies for 2010 to 2050. Paper prepared for the Pew/NCEP "10-50 Solution" Workshop. Washington, D.C., March 25–26, 2004, p. 2,

[23] Greene and Schafer, 2003.

[24] See *Greenhouse Gas Reporting and Disclosure: Key Elements of a Prospective Program.* In Brief, Number 3. Pew Center on Global Climate Change, Arlington, VA.

[25] Workshop participants asserted that companies can only "manage what they measure." In addition, programs such as state-level mandatory waste audits have been linked to reductions in waste generation at the company level through improved information.

[26] Well to wheels or "full fuel cycle" emissions refer to all the emissions involved in producing and using a fuel including: primary feedstock extraction, transport of the feedstock to a fuel production plant, fuel production, storage and distribution of fuel, and use of the fuel (for example, in a vehicle). See Ogden, Joan M. 2004. Hydrogen as an Energy Carrier: Outlook for 2010, 2030, and 2050. Paper prepared for the Pew/NCEP "10-50 Solution" workshop. Washington, D.C., March 25–26, 2004, p. 3.

[27] Although hydrogen can be used in stationary applications, the focus of the hydrogen-related analysis commissioned for the 10-50 Workshop was hydrogen in transportation applications.

[28] Raman, Venki. 2004. "Today there are many tens of hydrogen fuel stations in the U.S., Europe, and Japan serving very small numbers of hydrogen demonstration vehicles," quoted in Hydrogen Production and Supply Infrastructure for Transportation. Paper prepared for the Pew/NCEP "10-50 Solution" Workshop. Washington, D.C., March 25–26, 2004.

[29] See Ogden, 2004.

[30] Hydrogen can be made from a number of widely available primary energy sources, including natural gas, renewables, coal, and nuclear power. It also can be used in fuel cells and internal combustion engines with high conversion efficiency and essentially zero emissions of GHGs and conventional air pollutants. Therefore, if hydrogen is made from a zero-emission sources like renewables or fossil fuels with carbon capture and sequestration, it would be possible to produce and use fuels on a global scale with almost zero full fuel cycle emissions of GHGs and greatly reduced emissions of air pollutants. See Ogden, 2004, p. 1.

[31] Ogden, 2004, p. 11.

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[32] It is important to note that the EOR process does not necessarily involve long-term storage of CO_2. Studies are under way to determine what happens to the CO_2 after it is injected into geological formations in the EOR process.

[33] Each 1,000 MW plant emits and would need to sequester approximately 7–8 million tons of CO_2 per year (mtons/yr). Currently, the largest CCS project in the world (in Weyburn, Canada) sequesters 1.7 mtons/yr, and the largest planned project (in Gorgon, Australia) plans to sequester 4 mtons/yr starting in 2006.

[34] Burruss, Robert C. 2004. Geologic Sequestration of Carbon Dioxide in the Next 10 to 50 Years: An Energy Resource Perspective. Paper prepared for the Pew/NCEP "10-50 Solution" Workshop. Washington, D.C., March 25–26, 2004, p. 4.

[35] Deutch, John, Ernest J. Moniz, et al. 2003. *The Future of Nuclear Power—An Interdisciplinary MIT Report.* Massachusetts Institute of Technology. See http://web.mit.edu/nuclearpower/, p. 21.

[36] Three power companies are currently pursuing Early Site Permits for existing nuclear sites, with the intent to "bank" these sites for possible use in the future. The U.S. DOE is funding the three site banking projects on a 50/50 cost share basis. See Kray, Marilyn C. 2004. Long-Term Strategy for Nuclear Power. Paper prepared for the Pew/NCEP "10-50 Solution" Workshop. Washington, D.C., March 25–26, 2004, p. 5.

[37] Kray, 2004, p. 3.

[38] Moniz, Ernest J. 2004. Nuclear Power and Climate Change. Paper prepared for the Pew/NCEP "10-50 Solution" Workshop. Washington, D.C., March 25–26, 2004, p. 1.

[39] The once-through mode means removing the spent nuclear fuel for geological disposal. Closed fuel cycles are those in which the irradiated fuel is chemically processed to separate and recycle in the reactor components that have energy value, principally plutonium. See Moniz, 2004, p. 1.

[40] Hoffert, 2004, p. 16. See also Kammen, Daniel M. 2004. Renewable Energy Options for the Emerging Economy: Advances, Opportunities and Obstacles. Paper prepared for the Pew/NCEP "10-50 Solution" workshop. Washington, D.C., March 25–26, 2004, p. 1.

[41] Hoffert, 2004, p. 2.

[42] U.S. DOE, EIA. 2004. *Annual Energy Outlook 2004.* See http://www.eia.doe.gov/oiaf/aeo/electricity.html#elerene.

[43] Kammen, 2004, pp. 1-2.

[44] Hoffert, 2004, p.2; Kammen, 2004, p. 1.

[45] Most renewable resources are intermittent generation sources, i.e. their generation capacity is not constant and is subject to natural variability of such factors as wind speed and solar insolation.

[46] i.e., distance from areas of major electrical demand and lack of adequate transmission infrastructure.

[47] Hoffert, 2004, p. 3.

[48] Of the total percentage of electricity that would have to come from renewables under an RPS, a certain amount, or "set-aside," could be required from one source or technology (e.g., solar). Kammen, 2004, p. 4: "At present, wind is the cheapest form of renewable energy in many locations, and care needs to be exercised to open markets to a range of renewables such as in the Nevada RPS, where a specific set-aside exists for solar energy. Allowing regional differentiation could also be a significant benefit, so that biomass-rich regions such as the Southeast and Midwest, could adopt initial set-asides for biomass-based renewable fuels." Such a standard could be phased in over a period of years to take advantage of cost reductions as technologies develop. For example, an RPS could start at 3 percent initially, ramping to 5 percent a set number of years later, and so on with a relatively high number (e.g., 20 percent) established as the standard 20 years out. This could help minimize the costs of such a standard by avoiding significant investments in certain technologies before they are more cost competitive.

[49] Currently, the U.S. DOE's two primary areas of focus are (1) centralized coal electricity and hydrogen production with carbon sequestration, and (2) next generation nuclear reactors (Hoffert, 2004, p. 2).

[50] Forward funding is "a type of multiyear appropriation that is made available in the middle or toward the end of a fiscal year and remains available through the next fiscal year: for example, from July 1 of one year through September 30 of the next" (see http://www.house.gov/rules/glossary_fbp.htm). Forward funding removes some of the uncertainty, delay, and earmarking associated with the standard congressional appropriations process.

[51] MacNaughton, Joan. 2004. UK's 50 year energy strategy. Presentation to the Pew/NCEP 10-50 Workshop. See also Performance and Innovation Unit. 2002. *The Energy Review: A Performance and*

Innovation Unit Report—February 2002. Cabinet Office, London, UK. See http://www.number-10.gov.uk/su/energy/1.html.

[52] See Lempert, Robert J., Steven W. Popper, Susan A. Resetar, and Stuart L. Hart. 2002. *Capital Cycles and the Timing of Climate Change Policy*. Pew Center on Global Climate Change, Arlington, VA.

[53] See *Greenhouse Gas Reporting and Disclosure: Key Elements of a Prospective Program.* In Brief, Number 3. Pew Center on Global Climate Change, Arlington, VA.

[54] For more information about emissions trading, see Ellerman, A. Denny, Paul L. Joskow, and David Harrison Jr. 2003. *Emissions Trading in the U.S.: Experience, Lessons, and Considerations for Greenhouse Gases*. Pew Center on Global Climate Change, Arlington, VA.

[55] See Nordhaus, Robert R., and Kyle W. Danish. 2003. *Designing a Mandatory Greenhouse Gas Reduction Program for the U.S.* Pew Center on Global Climate Change, Arlington, VA.

[56] The figure is drawn from Greene, David L. 2004. Climate Change Policy for Transportation While Waiting for Hydrogen. Paper prepared for the Pew/NCEP "10-50 Solution" workshop. Washington, D.C., March 25–26, 2004.

[57] The explanatory arrows on this graph refer to policy actions that occurred during one year (bar) on the graph, but which had an effect on the next year (bar). For example, the PTC expired in 1999 during a capacity "boom" in the industry, which was subsequently followed by a "bust" in 2000. The California energy crises (and renewal of the PTC in 2000) was followed by another "boom" in 2001. Source: BTM Consult ApS (2004) International Wind Power Development World Market Update 2003: Forecast 2004–2008. BTM Consult ApS, Ringkøbing, Denmark, and Vestas Wind Systems. "International Context." Presentation at the Ontario Wind Policy Summit. Canadian Wind Energy Association. February 24, 2004. See http://www.canwea.ca/downloads/en/PDFS/Context_-_Session_1.pdf.

[58] Feed-in laws guarantee independent power producers (e.g., wind generators) a certain price for the electricity they provide to the grid. These prices are set by statute, and rate-payers pay the difference between the "feed-in" price and the average cost of electricity. See http://www.windworks.org/articles/fl_ElectricityFeedLaws.html. Source BTM Consult ApS (2004) and Vestas Wind Systems.

[59] MacNaughton, Joan. 2004. "UK's 50 year energy strategy." Presentation to the Pew/NCEP 10-50 Workshop. See also Performance and Innovation Unit. 2002.

[60] Holdren, John P. 2004. "Integrating Common Themes: Some Observations for the Workshop on Technologies and Policies for a Low-Carbon Future." 2004. Presentation to the Pew/NCEP 10-50 Workshop.

[61] See U.S. Green Building Council, http://www.usgbc.org/leed/leed_main.asp.

[62] Wimmer, Robert (Toyota Motor North America). 2004. "De-Coupling Business Growth Coupling Business Growthfrom Carbon Emissions from Carbon Emissions." Presentation to the Pew/NCEP 10-50 Workshop.

[63] See Smith, Douglas W., Robert R. Nordhaus, Thomas C. Roberts, et al. 2002. *Designing a Climate-friendly Energy Policy: Options for the Near Term*. Pew Center on Global Climate Change, Arlington, VA.

[64] Kenderdine, Melanie. 2004. "High Natural Gas Prices Could Impact Environmental Imperatives." Presentation to the Pew/NCEP 10-50 Workshop.

[65] Demand destruction refers to the temporary or permanent reduction in demand for natural gas usually caused by rising natural gas prices and usually referring to industrial sector demand for natural gas.

[66] U.S. DOE, EIA. 2004. *Annual Energy Outlook 2004*. See http://www.eia.doe.gov/oiaf/aeo/.

[67] Kenderdine, Melanie. 2002. Prepared Remarks of Melanie Kenderdine—6th Annual World Energy Experts Conference, Abu Dhabi, UAE, January 28–29, 2002.

[68] DARPA (the Defense Advanced Research Projects Agency) was established by the U.S. Department of Defense in 1958. Its initial mission was to coordinate the military's competing missile, space, and missile-defense programs. Its role has evolved to focus on three main areas: computers and information technologies, sensors and surveillance, and directed energy weapons. "Cloning" DARPA would require the replication of its clearly defined, well-accepted mission, autonomy, flexibility, and links with the best non-government research groups. See Alic, John A., David C. Mowery, and Edward S. Rubin. 2003. *U.S. Technology and Innovation Policies: Lessons for Climate Change*. Pew Center on Global Climate Change, Arlington, VA.

[69] Wimmer, 2004, slide 7, and Ogden, 2004, p. 13.

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Pew Center/NCEP 10-50 Workshop

Energy Efficiency Overview Paper

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I. Introduction

The purpose of this paper is to assess the possibilities for energy efficiency improvements in the United States over the next ten to fifty years. Energy use is the major contributor to greenhouse gas (GHG) emissions and any effort to bring GHG emissions under control will require considerable improvements in energy efficiency. In addition to reducing GHG emissions, energy efficiency can reduce peak electricity demands thereby reducing the need for new electrical capacity, contribute to reduced air pollution, and contribute to energy security to the extent that it reduces our reliance on foreign energy imports. Economic savings would also offset some of the costs of energy efficiency investments.

Business as usual scenarios suggest that U.S. carbon emissions will grow at an annual rate of 1.5 percent in the period between now and 2025. While predictions going out 50 years are risky and subject to considerable adjustment, a standard reference case is the 1.5 percent growth rate contained in the Energy Information Administration's *Annual Energy Outlook 2004*.

In this overview, I provide a "good news – bad news" story. The good news is that there is enormous technological potential for energy efficiency, and that energy use responds to changes in energy prices and policies such as efficiency standards. The bad news is that although technological potential is high, it is unclear how high prices will have to rise (or other institutional reforms will need to be undertaken) to bring about these changes. Therefore, it will likely require some combination of significant energy price increases, efficiency standards, efficiency labeling and other information campaigns, and institutional reforms in order to bring about large-scale improvements in energy efficiency.

II. Background

I begin by noting some trends in energy use over the past fifty years. Energy consumption in the United States has nearly tripled over that time period (see Figure 1). Declines in aggregate energy consumption are closely tied to the recessions of 1953-54, 1957-58, 1973-75, 1980, 1981-82, 1990-91, and 2001. Sharp reductions over short time periods occurred during the energy crises brought on by the Arab oil embargo in 1973 and the Iran-Iraq War of the early 1980s. In nearly all cases, energy use has quickly rebounded.

Figure 2 presents data on per capita energy consumption and real energy prices in the United States over this same period. The solid line is per capita energy consumption (legend on the left hand axis) while the dotted line graphs a real fossil fuel composite production price in dollars per million BTUs (legend on right hand axis). Rising energy use per capita peaked in 1978-79 and has stayed relatively constant since then. The large run up in energy prices in the 1970s blunted the upward momentum of per capita energy use and—despite the sharp fall-off in real energy prices since 1980—per capita energy use has not resumed its upward trajectory.

The most striking story is told in Figure 3 which graphs energy consumption per dollar of real GDP (together with the same overlay of the composite real energy price) from 1949 through to the present. Energy consumption per dollar of real GDP has fallen by over 50 percent since 1949. While it was falling prior to the first oil price shock, the decline in energy consumption relative to real GDP accelerated in the 1970s and has continued in the 1990s during a time of falling energy prices. An important question for research—and one which will critically inform recommendations for future enhanced energy efficiency—is the source of the dramatic improvement in energy use per dollar of GDP. The background paper on building energy efficiency for this conference (Loftness, 2004) hints at one possible answer to the question. Loftness cites work by Rosenfeld, Romm, Akbari and Lloyd (2004) that argues that California and national standards for equipment and appliance efficiency reduced overall energy consumption for heating, cooling, and refrigeration by from 25 to 75 percent. Figure 3 hints at another source of the gains. Energy consumption began its steady drop in 1971 just as energy prices stopped falling and began to rise—first slowly and then sharply. It may be that some of the efficiency gains that are attributed to efficiency standards would have occurred anyway in the higher energy price environment following the first oil price shock. A further complication arises from studies that emphasize the importance of structural shifts in demands for energy services (e.g., Schipper et al, 2001).

Last I note the large number of regulatory and informational initiatives that have been undertaken to encourage energy efficiency. Loftness notes the Leadership in Environmental and Energy Design (LEED) program of the U.S. Green Building Council. To obtain a LEED certification, a building project must satisfy a certain number of prerequisites related to site sustainability, energy efficiency, material and resource conservation, and indoor environmental quality. In addition to the building certification program, LEED provides resources to educate builders about constructing environmentally friendly and energy efficient buildings.

The U.S. EPA's Energy Star Program began in 1992 as a voluntary program to provide information to consumers about energy consumption of computers and other office equipment. It has expanded to include home appliances and other equipment. The logic behind the Energy Star Program is to provide information so that consumers can make educated appliance and equipment purchase decisions to trade off the (possible) increased purchase costs of energy efficient equipment against the lower energy costs of usage (see U.S. Environmental Protection Agency (2003)). The Energy Star Program subsumed the EPA's Green Lights Program in 1995. This program had been formed to work with the industrial and commercial sector to encourage energy efficient lighting in these two sectors. One component of the Green Lights Program was a contract between Green Lights Partners and the EPA by which partners agreed to install specified energy efficient lighting if the rate of return on the energy efficient investment exceeded a given rate of return.

Another initiative to encourage energy efficiency is described in the background paper on industrial energy efficiency for this conference (Price and Worrell, 2004). This is the U.S. Department of Energy's Industrial Assessment Centers, run by a number of universities across the country. The IAC database (housed at Rutgers University) contains data from some 12,000 assessments with over 82,000 recommendations for improvement.

In addition to the initiatives described above to encourage energy conservation and efficiency, Jaffe, Newell and Stavins (2001) report public-private partnerships in the area of housing (Partnership for Advancing Technology in Housing), schools (Energy Smart Schools), vehicles (FreedomCAR), and industrial processes (Best Practice, and the Office of Industrial Technology's Industries of the Future).

Finally, an important area in which the government has moved to limit energy consumption has been the development of mandatory appliance energy efficiency standards. The first standards were implemented in 1988 for clothes washers and dryers and dishwashers (see Table 1 in Jaffe, Newell and Stavins (2001) for a detailed listing through 2001).

III. The Energy Paradox

Two of the background papers for this conference are quite upbeat about the potential for long-run energy efficiency improvements. Price and Worrell cite studies suggesting long-term potential reductions in energy use in the industrial sector of between 30 and 65 percent. Loftness concludes that various initiatives "could trigger dramatic improvements in energy and environmental quality in the built environment." The background paper on the economics of energy efficiency (Newell, 2004), on the other hand, is less sanguine about the potential for large-scale energy efficiency improvements, noting that the benefits of any such gains must be weighed against the costs of achieving these gains. The difference in outlook reflects a long-standing difference in outlook between energy economists and energy technologists. As noted by Jaffe, Newell and Stavins (2001), this difference is well documented in the 1995 *Second Assessment Report of the Intergovernmental Panel on Climate Change*. Jaffe et al. note that "[o]ne part of this report states that energy efficiency improvements on the order of 10 to 30 percent might be possible at little cost or even with net benefits (ignoring climate benefits), while another part highlights the fact that most economic models indicate a significant cost for stabilizing or cutting OECD emissions below 1990 levels."

The difference in outlook between economists and technologists can be summed up in the concept of the "energy paradox." The energy paradox is the seeming anomaly that consumers pass up attractive energy efficiency investments with high *ex ante* rates of return (see Hassett and Metcalf (1993) for more discussion of this idea). But observing that people pass up what appear to be high return investments does not necessarily imply that there is a paradox. Part of the explanation comes down to differences in definition. Technologists often focus on technologies that have been proven in the laboratory. As Newell points out in his background piece, the process of technology acceptance involves three steps: *invention, innovation,* and *diffusion*. Each step is critically important to the acceptance of a new technology. According to Newell, invention "involves the development of a new idea, process, or piece of equipment." Technologists are often at the center of invention-related activity. Innovation is the step "in which new processes or products are brought to market." Innovation is the key step of making an invention commercially viable and may involve significant modification of the underlying technology. Note too that the commercialization aspect of innovation is such that the firm that spurs the technical breakthrough may not be the best skilled at taking it into the marketplace. The final step is diffusion, which is from Newell's explanation "the gradual adoption of new processes or products by firms and individuals, who then also decide how intensively to *use* new products or processes."

The innovation and diffusion processes can lead to significantly different efficiency gains than can be achieved in the laboratory. One study that illustrates this point (Metcalf and Hassett, 1999), used DOE data on energy consumption to measure empirically the returns to various home energy efficiency investments. This study found that realized returns were on the order of 10 percent—roughly one-fifth the estimated returns. One explanation for the lower returns is the difference in installation and utilization of energy efficiency capital between test houses and houses lived in by families. Insulation, for example, might not be installed optimally, and its benefits may be undermined by other characteristics of the house or family (ineffective windows or weather-stripping elsewhere, family inattention to open doors and thermostats, etc). This study suggests that additional measures such as consumer education should be considered when arguing for research investments in new technologies as a key tool for improving energy efficiency.

Studies of the diffusion of new technology find that adoption rates follow an S-shaped pattern with adoption beginning slowly, then rapidly increasing, and finally diminishing as the market becomes saturated. Newell's background piece alludes to a curious finding in a number of studies concerning the role of prices and the role of the upfront cost of the investment in efficiency in affecting adoption rates. Jaffe and Stavins (1995) studied the effects of energy prices and adoption costs on the adoption of new technology that increases the R-value in new home construction. R-value is a measure of the insulating properties of building materials. A house with a high R-value will use less energy than a house with a low R-value, other things held constant. While rising energy prices positively impacted the average R-value in new home construction, they found that equivalent cost subsidies were roughly three times as effective as price increases. This importance to consumers of reducing these upfront costs of energy efficiency is surprising given standard financial theory suggesting that a 10 percent permanent increase in energy prices should have the same effect on a cost-benefit analysis of an energy efficiency investment as a 10 percent reduction in the price of the investment.[1] Jaffe and Stavins's result is consistent with the view that consumers discount the future "too heavily." It is also consistent with other explanations. Hassett and Metcalf (1995) also found that tax credits that reduce the purchase price of new energy efficiency investments are roughly eight times more effective as equivalent increases in energy prices. The researchers speculate in that study that consumers may view the energy price increases as temporary in which case it is not surprising that one-time up-front cost savings are more effective than future (and risky) price savings.[2]

In addition to measurement problems (temporary versus permanent energy price increases, over-optimistic energy efficiency gains), other possible explanations of the Energy Paradox have been proposed. These include myopia, imperfect information, and capital market imperfections. To the extent that short-sighted behavior and imperfect or insufficient information are significant, information programs may be very helpful. As Newell points out, information is a public good and—like all public goods—will be under-produced in a competitive market. The government can play a key role with programs like energy labeling on appliances or office products.

One instrument that is not unambiguously welfare improving is energy standards. Energy standards have the effect of forcing consumers to purchase a minimal level of energy efficiency capital. In return for an increased upfront cost, the consumer receives future benefits in the form of energy savings. Let's say that the internal return on this investment is r^*. For consumers with a discount rate below r^*, this is a welfare enhancing investment. For consumers with discount rates above r^*, however, this is welfare reducing. Consumers with high discount rates are being forced to invest more than is optimal for them in energy efficiency. To the extent that high discount rates are disproportionately found among the poor, an appliance standards program will be regressive.[3] That standards may be regressive should not deter us from considering them. But we may wish to consider them as part of a larger package that combines progressive elements with this potentially regressive initiative (see Metcalf (1999) for a discussion of distributionally neutral green tax reforms).

Energy price fluctuations were noted above as one possible explanation for the dominance of purchase cost subsidies over energy price taxes as an instrument to induce greater energy efficiency investments. Energy price fluctuations raise the issue of uncertainty and sunk costs. An investment in energy efficiency is a risky investment given the uncertainty inherent in future energy prices. In addition, the investment involves sunk costs. Sunk costs are costs that cannot be recovered if a project is abandoned. Consider a factory manager considering investing in a new energy-efficient furnace. To the extent that the furnace is custom-designed for the specific factory, there is little resale value should the factory decide to "undo" the investment.[4] In the presence of return uncertainty and sunk costs of an irreversible investment, it is straightforward to show that the hurdle rate for investment rises with the risk. Hassett and Metcalf (1993) show some illustrations to demonstrate that diffusion of a new technology that has the properties of an irreversible investment and uncertain return can be dramatically slowed relative to a world with no uncertainty in the return to the investment. Metcalf and Rosenthal (1995) apply this methodology to investments in energy-efficient refrigerators and commercial fluorescent lighting. Given historic price variation in refrigerators and electricity, we estimated that the hurdle rate for new energy-efficient refrigerators is roughly 2.5 times what it would be in the absence of price uncertainty.

Summing up, there may be exciting technological developments that augur well for reducing energy use in the future. But there also exist a number of critical economic issues that suggest that the gains will not come as quickly or at as low a cost as we might otherwise think. I turn next to a brief discussion of the policy implications of this discussion.

IV. Policy Implications

Enhancements in energy efficiency can only be viewed as one piece of the puzzle for a plan to reduce carbon emissions in the United States. Given the uncertainties and difficulties attendant to many carbon reducing technologies, energy efficiency will be particularly important as one of the short to medium term contributors to reduced carbon emissions. As a general matter, any policy (whether it apply to energy efficiency or to other technologies) should be designed to be policy neutral between new energy supplies and efficiency. In other words, we should treat efficiency improvements as an energy source. A carbon tax or cap-and-trade system is an example of a policy that is neutral between efficiency and clean carbon sources. A subsidy to renewables and/or nuclear only is not.

The Energy Information Agency's Annual Energy Outlook 2004 projects carbon emissions to grow from 1,563 million metric tons per year in 2002 to 2,221 million metric tons in 2025, an annual growth rate of +1.50 percent. Consider as an example, a target for the United States to reduce its emissions to 1990 levels by 2015. Taking 2002 as the reference point for future emission reductions, emissions would have to decrease by -1.04 percent per year over the 13 year period (see Figure 4). Sutherland (2000) reports that the high technology assumptions contained in the "Five Lab" Study would only reduce the growth rate of emissions from +1.50 percent from the Annual Energy Outlook 1998 prediction to +0.56 percent. Therefore, even an optimistic assessment of energy efficiency options, finds that in the near-term technology alone will not stabilize carbon emissions in absolute terms.

My reading of the historic improvements in energy efficiency over the past 30 years leads me to conclude that a combination of price based instruments along with quantity based instruments (e.g. standards) will provide the most effective gains in energy efficiency in the near-term. In both cases, a key component of the policy is that carbon is priced. Let me discuss these in turn.

Taxes are the most obvious price-based instrument. One rationale for moving to a greater reliance on carbon or energy taxes is that the United States taxes energy much more lightly than other developed countries. The possibilities include a carbon tax, a BTU tax, as well as more specific fuel taxes, for example, an increased federal excise tax on gasoline. A tax on carbon is the most efficient way to bring about reduced carbon emissions as the tax is precisely targeted to the externality of concern (GHG emissions).[5] A carbon tax has the disadvantage, however, that it raises the price of coal significantly relative to other fuels. While desirable from an environmental perspective, this price differential has adverse political and distributional implications that serve as a barrier to the use of carbon taxes.

The current political climate, in my view, is not likely to look favorably on *any* form of energy taxation in the United States. This despite the fact that energy taxes could offset some of the revenue losses from recent changes to the tax laws (see Metcalf (1999) for a discussion of revenue neutral green tax reforms).[6] This suggests that we should look at quantity based instruments.

Quantity instruments include non-tradable pollution quotas, tradable emissions permits (like the SO_2 permit program under the Clean Air Act Amendments of 1990), and performance standards (appliance standards, CAFE, etc.) In choosing how to design an effective and politically viable permit system, two questions must be answered. First, will the permits be given away (as under the electric utility SO_2 program) or will they be sold? In a world with pre-existing tax distortions, there are large efficiency losses resulting from giving away permits rather than selling them.[7] In brief, the revenues from selling the permits can be used to lower other distortionary taxes. Bovenberg and Goulder (2001) show that only a small fraction of the permits need be given to the energy producing industry to compensate for the loss in equity value for the firms following a decision to restrict carbon emissions. This follows because permits create barriers to entry (since you need a permit in order to operate if your firm emits pollution) and barriers to entry in turn create economic profits (or rents).

Second, will be permits be tradable? The primary benefit of trading is that a given level of pollution reduction can be achieved at lowest cost given the ability of heterogeneous firms to trade with high cost firms purchasing permits from low cost firms. Trading is counter-indicated when pollution can lead to "hotspots," areas of intense pollution. While an important issue for air pollutants in urban areas, this is not a relevant concern for carbon emissions given the mixing of carbon and other GHGs in the atmosphere. Thus a permit program should allow trading.

Starting with a modest cap (low price) and a consistent, pre-announced commitment to tighten the cap over 10-20 years (thereby raising the price) would give industry time to prepare for it while minimizing short-term resistance. Prior to its implementation, support for voluntary programs (like the Chicago Climate Exchange) should be provided. Also, it is worth studying whether a U.S. cap and trade system should allow for international buy-in on some level. This might simply allow firms to substitute foreign carbon reductions for domestic carbon reductions. For this to be feasible, firms would have to agree to more extensive measurement activities to create more comprehensive baselines for carbon emissions. This has the benefit for multinational firms to encourage them to engage in world-wide carbon audit measurement activities.

Performance standards in the industrial, transportation and building sectors that mandate a level of energy efficiency are politically attractive given the resistance to taxes or to programs that might require firms to purchase pollution permits. Loftness (2004) argues that due to a historic lack of policy attention and the diffuse nature of energy use in buildings, targeted standards (e.g., cool roofs, daylighting and natural ventilation) could provide significant reductions in national energy use. Performance standards in the industrial sector would likely have to be fine-tuned for individual industries. Strengthened CAFE standards are an attractive option for the transportation sector. Despite the fact that CAFE standards only apply to new vehicles (while gasoline taxes apply to new and used vehicles), research suggests that CAFE standards are much more effective at reducing fuel consumption than gasoline taxes (see Goldberg (1998) for evidence on this point).

In addition to the above policies, simple policies to raise awareness of energy consumption and carbon emissions would be low-cost but valuable policy instruments. Labeling the embodied carbon content in consumer products (or buildings) is an example of a policy to raise awareness. Promoting research to develop consistent measures of taxes and subsidies to energy production is another way to promote awareness. A federal policy requiring firms to engage in carbon audits (as some states do now in the environmental area) is a third low-cost policy. Interestingly, research in environmental economics suggests that state laws that mandate waste audits (with no requirement for remedial action) lead to waste reduction in the production process. The information gained through the audits is a valuable input used in production to bring about reductions in environmental waste (see Snyder, 2003).

In the longer-term, price increases have the potential to induce technological innovation that brings about further energy improvements. Using data from 1960-1990, Newell, Jaffe and Stavins (1999) found substantial evidence for price-induced technological change for a variety of appliances. Popp (2002) has found that energy-efficiency patent applications are positively correlated with energy prices. To strengthen the importance of induced technological change as we move forward in time, one approach promoted in the Loftness and the Price-Worrell background papers is to invest more money in R&D for energy-efficiency technologies. As a cautionary note, however, it should be noted that rate of speed of technology diffusion is retarded as capital stock service lives lengthen. Jaffe, Newell and Stavins (2001) note that the typical service life of commercial and industrial buildings is 40 to 80 years. While many efficiency opportunities are achievable through retrofit (and debate continues over the overall potential for retrofitted efficiency measures), even greater efficiency gains occur as the capital stock turns over (i.e., new construction, new equipment offer greatest opportunity vs. retrofitting). The background paper by Loftness provides exciting examples in the longer-term of potential reductions in energy use in buildings, and even the use of buildings as power plants in a distributed system.

V. Conclusion

Significant price changes, combined with regulatory and information policies to overcome market failures, will likely be required to bring about large-scale reductions in carbon emissions through improved energy efficiency. Price increases for energy or price reductions for energy efficient capital investment will bring about reductions in energy use;

whether these can be brought about at a low cost to the economy, however, remains to be seen. Evidence to date suggests that this will be unlikely at least in the short term.

Over the longer term, price signals have the potential to induce innovation that speeds up technological change. Even with significant technological change, however, we must recognize that it will be a slow process to replace the current energy inefficient capital stock, particularly for long-lived assets like buildings. Over the fifty year horizon we can expect to see significant efficiency improvements. In the near term, a combination of taxes, tradable permit schemes, and performance standards are the best options for bringing about increases in energy efficiency. Over the longer term, induced innovation resulting from price increases combined with strategic research and development investments can bring about greater energy savings and improvements in energy efficiency.

Note: Data source for figures: EIA (2003), *Annual Energy Review 2002*, Energy Information Administration, U.S. Department of Energy, Washington DC.

Figure 1. U. S. Energy Consumption

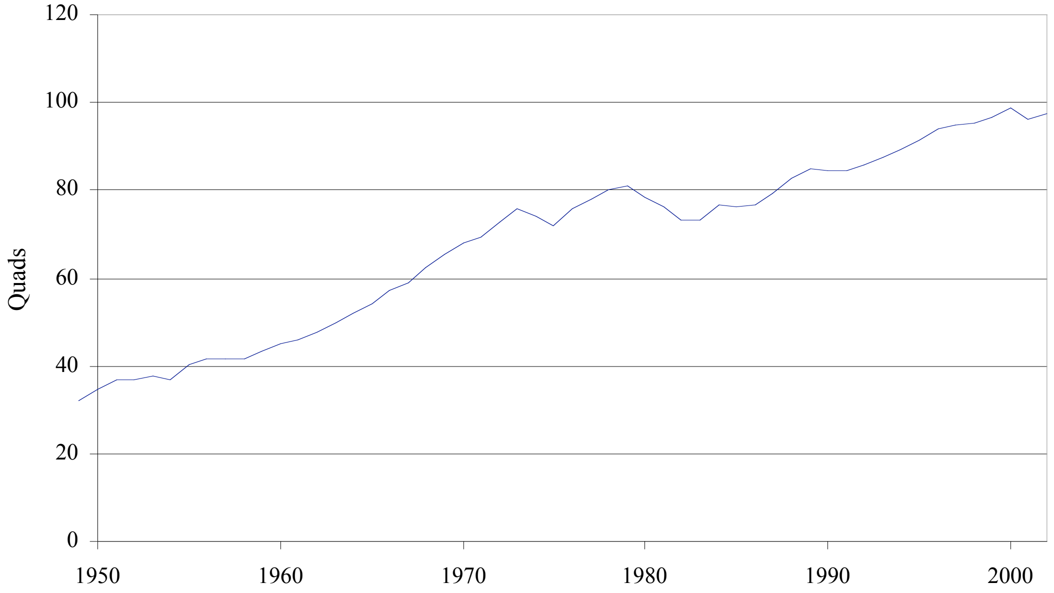


Figure 2. U. S. Energy Consumption Per Capita and Real Energy Prices

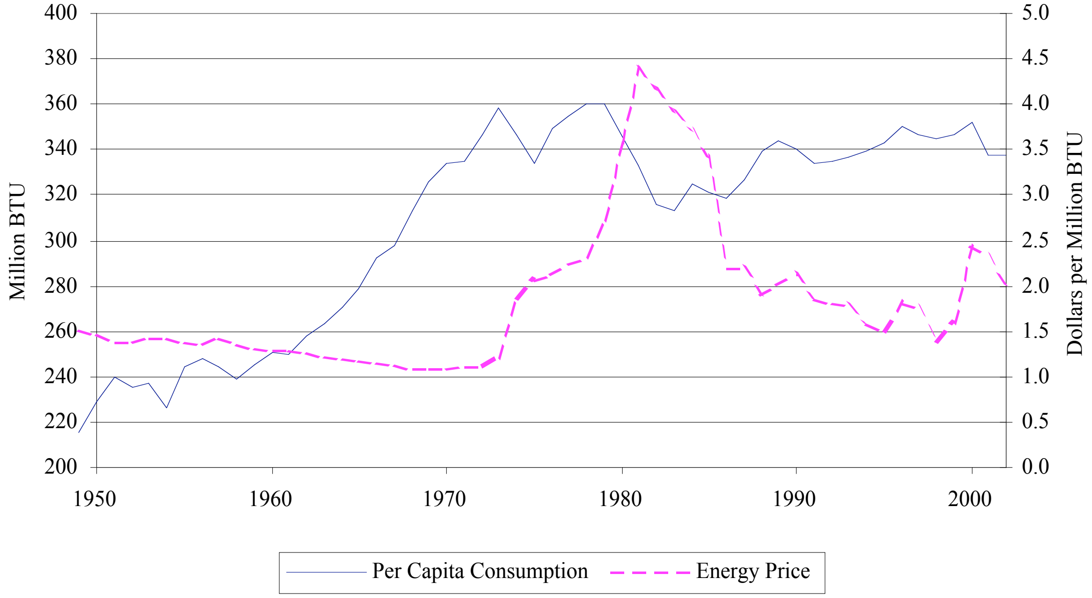


Figure 3. U. S. Energy Consumption per GDP and Real Energy Prices

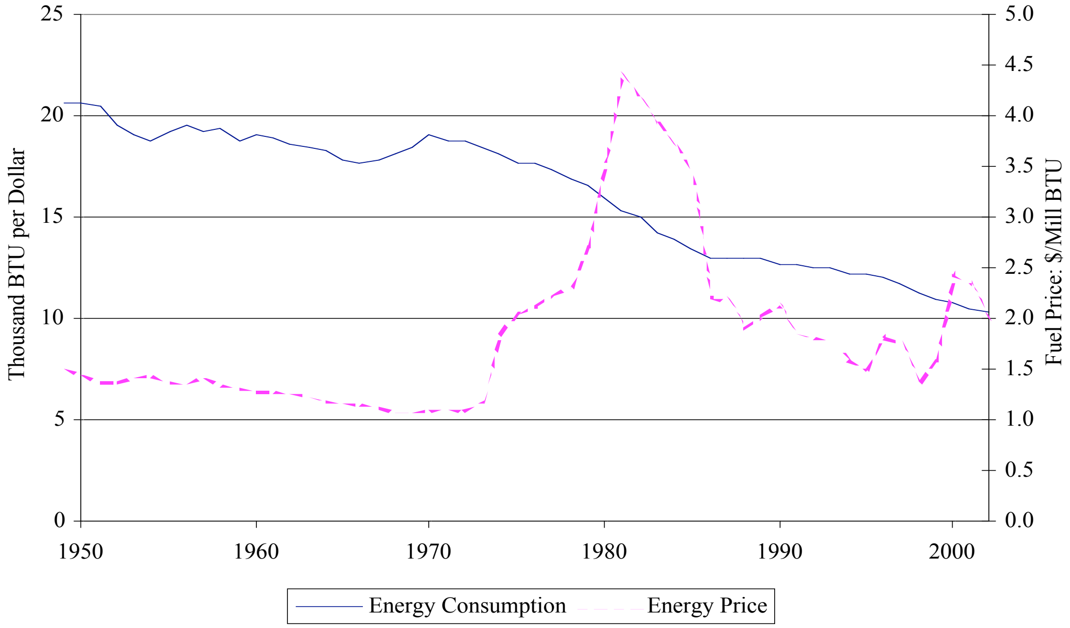
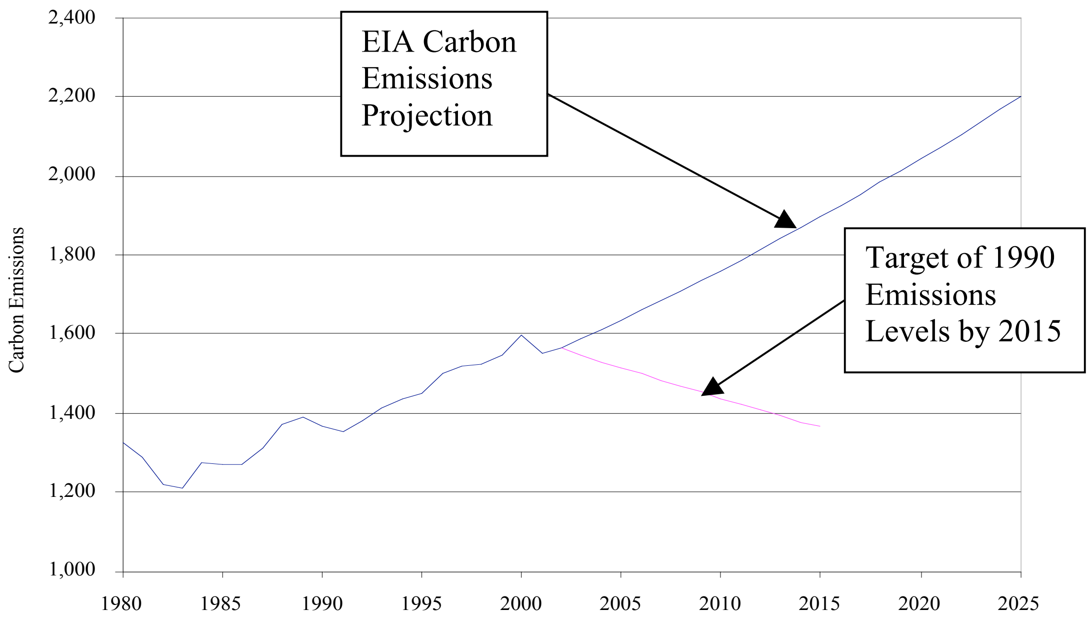


Figure 4. U.S. Carbon Emissions



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[1] This is true as a first-order approximation.

[2] While providing subsidies to energy efficient capital investments may have a greater bang for the buck to induce investment, it does not provide any incentive to reduce energy use with existing capital.

[3] Train (1985) documents the long-standing finding for higher discount rates among low-income people. Poorer access to capital markets and lower levels of education are two oft-cited reasons for this finding. Sutherland (1991) provides a CAPM analysis for why the poor might exhibit a high discount rate for energy efficiency investments.

[4] This is exacerbated by costs of customization and installation over and above the capital cost of the furnace itself.

[5] Fullerton, Hong and Metcalf (2001) discuss the welfare costs of imperfectly targeted environmental taxes.

[6] With estimates of the ten year budget deficit now approaching $2.4 trillion (Congressional Budget Office (2004)), there may be a softening of the opposition to energy taxes.

[7] See the discussion in Goulder, Parry and Burtraw (1997) and Fullerton and Metcalf (2001) on this point.

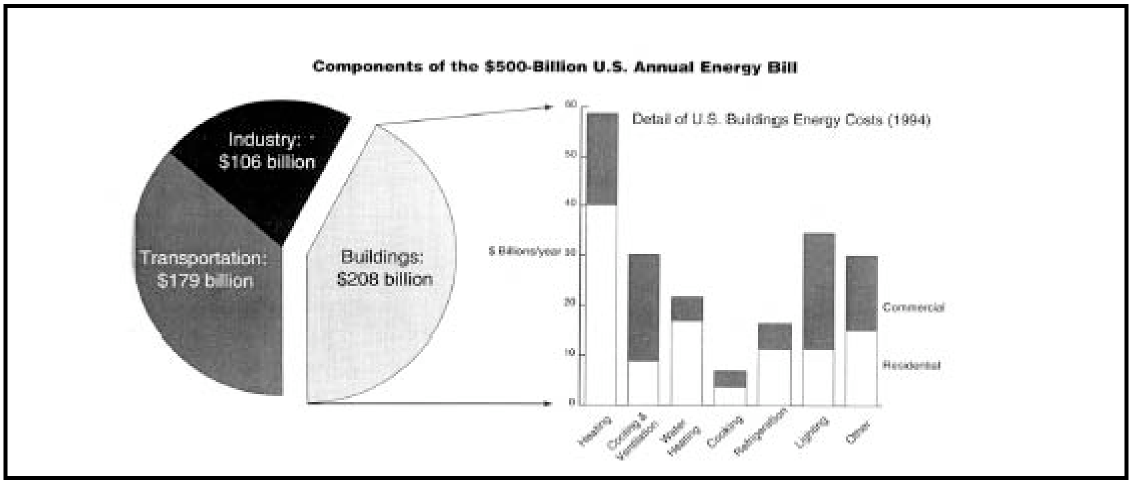
Improving Building Energy Efficiency in the U.S:
Technologies and Policies for 2010 to 2050

Prof. Vivian Loftness, Carnegie Mellon University

1.0 The Significance of Building Energy Use

The building sector is the biggest 'player' in the energy use equation and can have the greatest impact on addressing climate change (Figure 1, 1997 Interlaboratory Working Group). The U.S. Green Building Council has summarized the energy and environmental importance of this sector of the economy: Commercial and residential buildings use 65.2% of total U.S. electricity and over 36% of total U.S. primary energy. Buildings use 40% of the raw materials globally and 12% of the potable water in the United States. Building activity in the U.S. also contributes over 136 million tons of construction and demolition waste (2.8 lbs/person/day), and 30% of U.S. greenhouse gas (GHG) emissions (USGBC 2001).

Figure 1 (Interlaboratory Working Group 1997)



Illustrating the scale of the impact that building energy efficiency can have on national goals—if improved standards for residential refrigerator efficiencies had not been introduced in 1975, over 40 GW of additional power plant generation would have been needed in 2001, producing 32 million tons of carbon (MTC). Of equal importance, EER standards for commercial rooftop and residential air conditioners have avoided 135 GW of peak electricity load with associated carbon savings of over 100 MTC (Rosenfeld et al 2004).

The building sector currently receives the least federal attention for research and development, despite its large potential for addressing climate change through: reducing primary energy requirements and emissions, replacing fuel sources with non-carbon based alternatives, and supporting effective sequestration of carbon in the built environment.

2.0 Four specific directions in building energy efficiency

An evaluation and international comparison of the energy load breakdowns in residential and commercial buildings reveal substantial opportunities for energy efficiency in the building sector. While it is not possible to give a comprehensive list of these opportunities, the following paragraphs illustrate the potential impacts of four specific directions for building energy efficiency in both the 2010 and 2050 time horizons.

2.1 Appliance and equipment energy standards and innovations

The introduction of California and then national standards for equipment and appliance efficiency has had a major impact on national energy use, reducing energy consumption for heating, cooling and refrigeration demands by 25%, 60% and 75% respectively (Figure 2a, Rosenfeld et al. 2004). The direct relationship of appliance electricity demand and CO_2 production illustrates the value of these energy savings in addressing climate change. The impact of both R&D and standards has enabled refrigerator size and amenities to increase while overall energy use is reduced (Figure 2b, Rosenfeld 2004). Four pending appliance standards (clothes washers, fluorescent light ballasts, water heaters and central air conditioners) are projected to save consumers $10 billion in energy costs, improve functionality, and reduce cumulative emissions by as much as 22 MTC through 2010 (US Climate Action Report 2002). The natural replacement cycle of just four building technologies – ballasts, lamps, windows and refrigerator/freezers – with high performance alternatives would save 190 billion kWh of power demand (and 52 MTC) by 2010, with an additional 130 billion kWh (and 35 MTC) saved by 2050. There are few engineering obstacles and significant export growth potential in expanding appliance and equipment energy efficiency standards to cover the full range of existing and new equipment being introduced in residential and commercial buildings.

2.2 Shading, Cool Roofs and Cool Development

6% of all US energy is used in cooling residential and commercial buildings (Figure 3, Koomey 1996), at an annual cost of $40 billion, and peak power demands of 250 GW. A 5°F rise in neighborhood temperatures – from excessive absorption of solar energy in our increasingly impervious built environment (due to increases in roads, parking lots and roofs) – considerably increases cooling loads. On a national level, the creation of “cool communities” with white roofs, pervious paving, and shade trees would yield a 10% reduction in annual cooling loads, and a 5% reduction in peak cooling loads (Rosenfeld et al 2003). Moreover, CO_2 would be sequestered more effectively by urban trees than an equivalent number of new ‘forest’ trees, and urban flooding would be greatly reduced. In addition to the visible enhancement of our physical environment, cool community planning would yield a 6-8% reduction in smog with commensurate gains in the health of our citizens. Given the cycle time of roof replacements and tree growth rates, immediate federal and state policies and incentives are needed to realize the benefits of “cool communities” by 2020.

2.3 Daylighting and Natural Ventilation

Over 10% of all U.S. energy is used for lighting buildings, much of this during the daytime when daylight is abundant. In combination with the 6% of all U.S. energy used for cooling buildings in summer and winter, there is significant argument for the environmental benefits of windows for daylighting and natural ventilation. Given the dominant number of existing buildings – schools, hospitals, offices, manufacturing facilities – originally designed for effective daylighting and natural ventilation, the erosion of natural conditioning is a serious energy cost to the nation. Effective daylighting can yield 30-60% reductions in annual lighting energy consumption, with average energy savings for introducing daylight dimming technologies in existing building at over 30% (Loftness 2002). Emerging mixed-mode HVAC systems, that interactively support natural ventilation or air conditioning, are demonstrating 40-75% reductions in annual HVAC energy consumption for cooling. The effective use of natural conditioning with well designed windows, window controls, and mechanical and lighting system interfaces, promises to yield major energy efficiency gains of up to 5% of all U.S. energy use, reduce risk in power outages, and provide measurable productivity, health and quality of life gains.

2.4 On-site generation, the 'Building as Power Plant'

There are two major arguments for distributed energy systems, particularly the development of on-site energy generation that uses neighborhoods and campuses to ensure system efficiencies. First, U.S. transmission and distribution losses alone totaled 201TWh in 2002, or 55MTC per year. Second, the reject energy from power generation is a prime resource for building energy loads through co-generation of steam, chilled water via absorption chillers, desiccant conditioning, and hot water demands. This co-generation of power and building conditioning dramatically improves power generation efficiencies, from averages of 30% to well over 70% (WADE 2002). Add to this distributed renewable energy sources such as photovoltaic, solar thermal, fuel cells, micro-turbines or biomass, and buildings can actually become power plants – generating more power than they consume (Hartkopf 2002). The United States has a limited program in distributed energy systems, with too small a federal investment in combined heat and power technology to support research of CHP linked to renewable sources or CHP fully integrated with buildings and campuses. By 2050, each new building completed should be a net energy exporter – a building as power plant – with a diversity of renewable fuel sources as input (hydrogen, geothermal, solar thermal, solar electric, wind) and a building conditioning cascade that eliminates generation losses.

3.0 Actions for building energy efficiency and interrelated benefits

In addition to the obvious benefits of reduced energy demand, dramatically accelerated national investments and policies focused on building energy efficiency will contribute to:

- Reduced emissions and climate change impacts

- Increased peak power capacitance and reliability
- Improved health, human safety and security
- Improved productivity
- Improved quality of life
- Increased exports - products and services
- Setting a proven example for developing nations

With regards to mitigating against climate change, Greg Kats argues in a study of the costs and financial benefits of green buildings "The vast majority of the world's climate change scientists have concluded that anthropogenic emissions – principally from burning fossil fuels – are the root cause of global warming. The United States is responsible for about 22% of global GHG emissions. Of this 22%, the U.S. building sector is responsible for about 35% of US CO_2 emissions, the dominant global warming gas" (Kats 2003). In addition to energy efficiency gains, building and infrastructure revitalization can have a major impact on reducing urban sprawl and the consequent rapid increases in transportation energy use and emissions from single occupancy vehicles. The critical actions needed to advance building energy efficiency to meet both readily achievable goals in the short term as well as visionary goals in 2050 and beyond include changes in policy, investment and research at the federal, state and industrial level.

3.1 Policy – The market will not take care of it

Energy is cheap, especially if the externalities of pollution, risk, and health are considered. Consumers do not see energy as a large enough component of their disposable income to evaluate the Return on Investment (ROI) of energy efficiency in the built environment. Deregulation has already reduced the efforts of major utilities to pursue demand side management and weatherization, programs that will have to be picked up by the already budget constrained States. At the same time, power unreliability concerns may lead residential and commercial building owners to purchase inefficient and polluting standby power rather than consider the significant opportunity to invest in energy efficiency. The contributions of buildings to the discharge of four primary pollutants – NO_X, SO_X, CO_2, and particulates – should be fully recognized in the cost of building energy, to catalyze owners and occupants to pursue more environmentally responsible buildings and building use patterns.

Federal and state energy efficiency standards as well as tax incentives are critical. A remarkable example of environmental gain through policy, especially in today's under-regulated, under-incentivized market, has been the introduction of Leadership in Environmental and Energy Design (LEED) by the U.S. Green Building Council. The LEED rating utilizes certification to establish a building's environmental sustainability level related to: sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality and innovation in design practices. LEED goals have been adopted by a growing number of major building decision makers in the public and private sector impacting an estimated 3% of new construction with over 50% energy efficiency savings—gains that should be widely adopted.

3.2 Balancing investment in supply and demand

Given the major energy excesses in the built environment, reducing demand must be seen as a major energy <u>source</u>. Investments in "mining" this new energy supply will: yield greater economic benefit for a broader array of industries; provide significant gains in reducing environmental pollution; and ensure a longevity to this "supply" that few other sources can ensure. Unfortunately, the continued federal dollars going into R&D for energy supply outweigh R&D dollars for energy demand 6 to1 (DOE/CR-0059 1999), even though the ROI of energy efficiency dramatically exceeds the ROI of creating new sources. For example, the modest national investments (of around $3M per program) by DOE in R&D for energy efficient ballasts, low-E windows, and refrigerator standards, reaped national benefits of $9,000, $7,000 and $23,000 <u>per dollar</u> invested (Rosenfeld 2004).

3.3 Building Research – An unrecognized federal mandate

Investing in building energy efficiency as a new energy "supply" would dramatically surpass production from new oil supplies and power plant investments, as well as offer sustained "sources" of energy that do not generate greenhouse gases. Yet the combined budgets for building research across the federal government is less than 2% of federally funded R&D, in no way commensurate with the importance of the built environment to our economy and quality of life (Loftness/NSF 2000). Given this paucity of research support, there are only a handful of university Ph.D. programs focused on energy efficiency and environmental quality in the built environment, compared to many dozens of universities with federally funded research related to nano-technology and information security for example. Given that the building sector is 20% of the U.S. economy, over 35% of U.S. energy use and associated environmental quality, and significantly linked to the health and competitiveness of our nation, the federal sector must move beyond today's marginal funding of research in the built environment.

4.0 Conclusions

Energy efficiency in buildings represents a major untapped resource for our energy demands and resultant mitigation of climate change. Standards and removal of market barriers can lead to significant reductions in energy use from key buildings technologies through their natural replacement cycle. A 1997 study undertaken by all five national laboratories determined that building energy efficiency could achieve 230 MTC of the 400 MTC savings needed by 2010 to meet U.S. targets under the Kyoto Protocol. With the addition of innovative combined cooling, heat and power technologies, a further 170 MTC could be achieved, fully meeting 2010 goals through the building sector alone. Over the longer term, expanded building R&D budgets, industry and university based research, and continuing national policies that focus on building energy efficiency, could trigger dramatic improvements in energy and environmental quality in the built environment. Moreover, these investments would ensure ancillary benefits including revitalization of existing buildings and infrastructures, measurable gains in health and productivity, and a positive influence on energy efficient growth in the built environment of developing nations.

In December 2002, the EU adopted the Directive on Energy Efficiency of Buildings with the goal of cost-effective energy savings of 22% by 2010 through four basic actions (Bowie & Jahn 2003):

1. General framework for a methodology of calculation of the integrated performance of buildings.
2. Setting of minimum standards in new and existing buildings.
3. Energy certification of buildings
4. Inspection and assessment of heating and cooling installations.

The United States needs to enact parallel efforts to ensure that the long term implications of decision making in the built environment contribute to our energy, carbon and pollution mitigation, and quality of life goals. With the right policies, incentives and research, building energy efficiency can have a 20%-50% impact on building energy use by 2010, and a 75% impact by 2050, outpacing both the industrial and transportation sectors in national energy savings.

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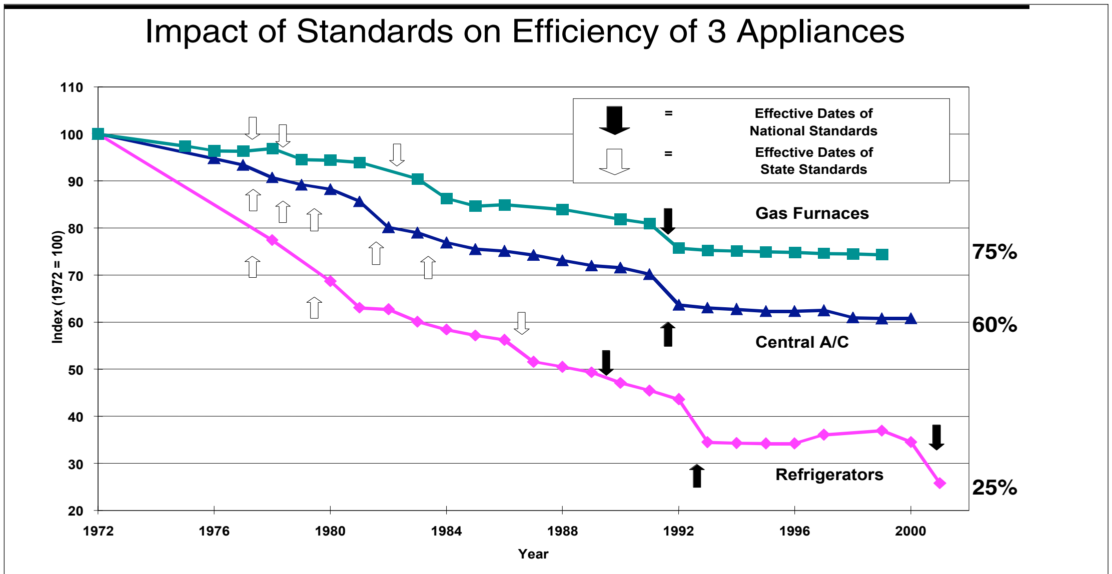
Figures 2a, 2b (Rosenfeld et al 2004)


Impact of Standards on Efficiency of 3 Appliances

Source: S. Nadel, ACEEE, in ECEEE 2003
Summer Study, www.eceee.org

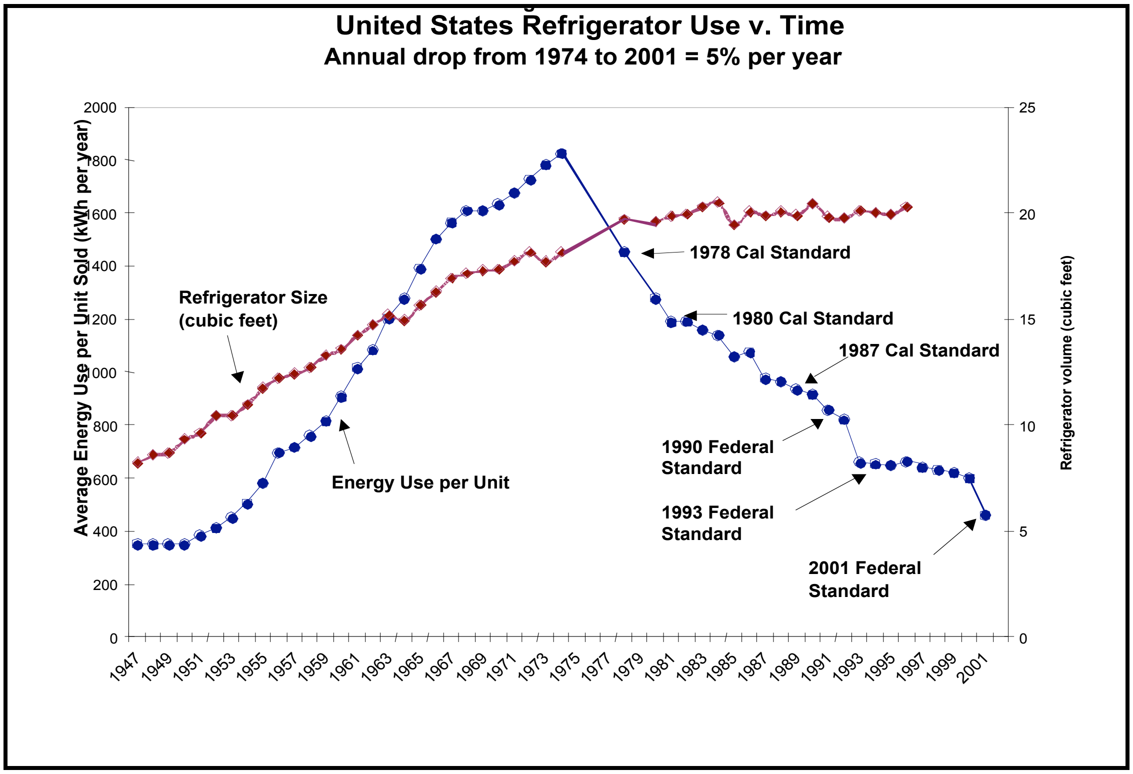

United States Refrigerator Use v. Time
Annual drop from 1974 to 2001 = 5% per year

Figure 3 (Koomey 1996)

Figure 1: U.S. residential sector carbon emissions by end-use 1990 (million metric tonnes of carbon)

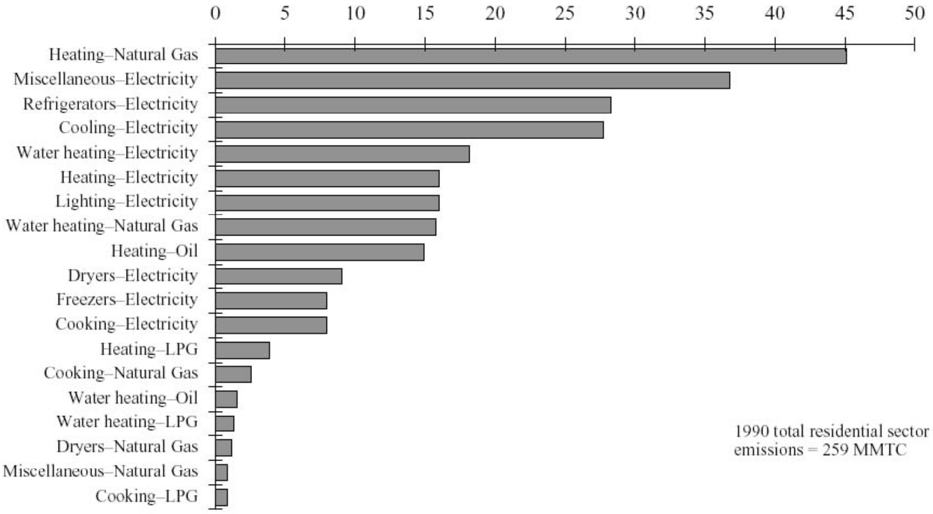
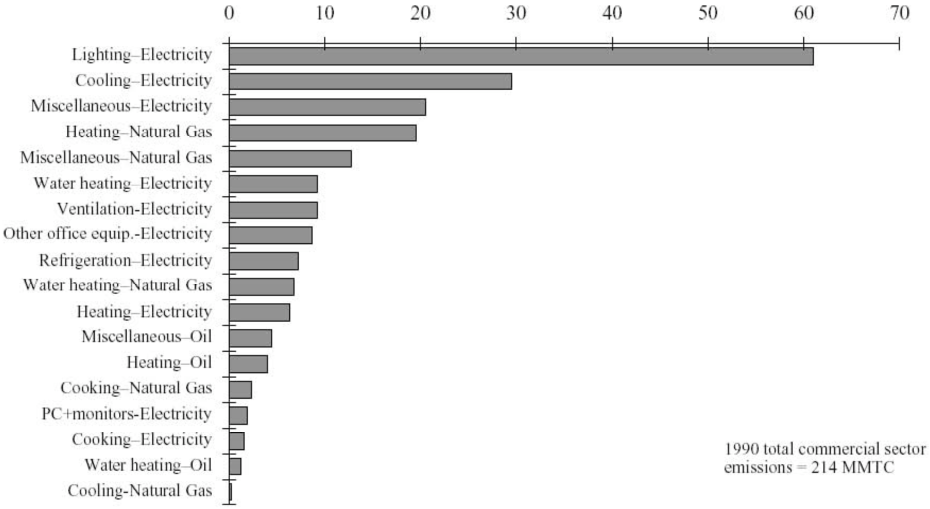


Figure 2: U.S. commercial sector carbon emissions by end-use 1990 (million metric tonnes of carbon)



Pew Center/NCEP 10-50 Workshop

Energy Efficiency Challenges and Policies

Richard G. Newell, Resources for the Future

I. Introduction

As with virtually all economic problems, the economics of energy efficiency is at its heart a question of balancing of costs and benefits. For the individual energy user, this involves weighing the higher initial cost of purchasing more energy-efficient products with the expected benefits of future energy operating cost savings, among other considerations. For suppliers of energy-using products, decisions regarding energy-efficient innovations likewise depend on the expected profits from such technology development. Profits from innovation depend in turn on the expected demand for energy-efficient technologies and the degree to which firms can appropriate the value created by their innovations.

On both the demand and supply side of this market for energy-efficient technology there are potential market imperfections that can lead to under-investment in energy efficiency. This raises the possibility that corrective government policies could provide economic gains and provide net benefits after inclusion of all public and private implementation costs. The degree to which such opportunities exist in practice is the subject of significant debate. Environmental pollution associated with energy production—particularly carbon dioxide (CO_2) emissions from fossil fuels—represents an additional reason why private markets might under-provide energy efficiency if energy users do not face the cost of any resultant environmental harm.

II. Energy-efficient technological change

To understand the potential for public policy to affect energy efficiency, it is useful to understand the process through which technology evolves: invention, innovation, diffusion, and product use. *Invention* involves the development of a new idea, process, or piece of equipment. This activity typically takes place inside the laboratory. The second step is the process of technology *innovation*, in which new processes or products are brought to market. Another way of describing this stage is commercialization. The third step is *diffusion*, the gradual adoption of new processes or products by firms and individuals, who then also decide how intensively to *use* new products or processes.

Beginning at the end of the technological change process, research has consistently shown that diffusion of new, economically superior technologies is never instantaneous. An S-shaped diffusion path is typically used to describe the progress of new technologies making their way into the marketplace. The explanation for this typical path of diffusion that has most relevance for energy-conservation investments is related to differences in the characteristics of adopters and potential adopters. This includes differences in the type and vintage of their existing equipment, other elements of the cost structure (such as access to and cost of labor, material, and energy) and their access to technical information. Such heterogeneity leads to differences in the expected returns to adoption and, as a result, only potential adopters for whom it is especially profitable will adopt at first. Over time, however, more and more will find it profitable as the cost of the technology falls, its quality improves, information about the technology becomes more widely available, and existing equipment stocks depreciate. The longevity of much energy-using equipment reinforces the importance of taking a longer-term view toward energy-efficiency improvements—on the order of decades.

Several studies have explored the effect of energy prices and technology adoption costs on energy-efficiency investments. From a policy perspective, the effect of higher energy prices can be interpreted as suggesting what the likely effects of taxes on energy use (and CO_2) would be, and the effects of changes in adoption costs can be interpreted as indicating what the effects of technology adoption subsidies would be. As one might expect, these studies have typically found that higher energy prices increase, and adoption costs decrease, the extent of adoption of energy-efficient technology (e.g. building insulation, more efficient home appliances, more efficient industrial motors).

An additional interesting finding in this line of research is that the adoption of these technologies is more sensitive to the cost of the equipment than it is to the expected cost of energy. This would seem to imply that a policy of subsidizing the purchase of new efficient equipment may be more effective than a policy of taxing resource use, for policies that should in theory create the same magnitude of economic incentive. This interpretation is subject to debate, however, and it is important to recognize some disadvantages of such subsidy approaches. First, unlike energy prices, adoption subsidies do not provide incentives to reduce utilization. Second, technology subsidies and tax credits can require large public expenditures per unit of effect, since consumers who would have purchased the product even in the absence of the subsidy (i.e., "free-riders") still receive it. In addition, studies that have investigated directly the effect of income tax credits on energy-efficient technology adoption have found mixed results.

As with technology diffusion, studies have shown that increases in the price of energy have induced technological innovations in energy efficiency of commercialized products, such as household appliances (e.g., air conditioners, water heaters), automobiles, tractors, and jet aircraft. Moving back even further in the process of technological change to examine invention, other studies have analyzed U.S. patent data, finding that the rate of energy-conserving patent applications (e.g., for waste heat, heat pumps, solar energy, fuel cells) is significantly and positively associated with the price of energy.

III. Market failures and policy responses

At a conceptual level there are several reasons why technology diffusion will not, in general, occur at an economically efficient rate. Those market barriers that might justify a public policy intervention to overcome them are referred to in economics parlance as "market failures". Normative economics teaches that in the presence of market failures, unfettered markets may not operate to produce outcomes that are socially optimal. When analysts speak of no-cost climate policies based on energy efficiency enhancement, they are often implicitly or explicitly assuming the presence of market failures in energy efficiency.

There are several sources of potential market failure that may affect energy-conserving technology adoption rates. Three of these relate to the availability of information, and the others relate to environmental externalities, and broader innovation and adoption externalities. Energy supply pricing and national security may also be an issue.

Inadequate information. First, information has important "public good" attributes: once created it can be used by many people at little or no additional cost. It may be difficult or impossible for an individual or firm that invests in information creation to prevent others who do not pay for the information from using it. It is well known that such public goods will tend to be underprovided by ordinary market activity. Second, if the act of adopting a new technology is, itself, a source of useful information for others, then the act of adoption creates a positive externality by providing information to others for which the adopter is unlikely to be compensated. Third, incomplete information can also foster "principal-agent" problems, as when a builder or landlord chooses the level of investment in energy efficiency in a building, but the energy bills are paid by a later purchaser or a tenant. If the purchaser has incomplete information about the magnitude of the resulting energy savings, the builder or landlord may not be able to recover the cost of such investments, and hence might not undertake them. This is another potential form of market failure.

Product testing and labeling, general and professional education programs, and energy audits are potential policies that have been used in practice to address these information problems. Minimum energy efficiency standards also address the information problem, in a sense, by removing the need for the purchaser to analyze the efficiency decision, at least at the lower end of the efficiency spectrum. In a sense, one can think of efficiency standards as economizing on the need for energy efficiency analysis by all individuals, since the government does it once for everyone. But the reality is that if the assumptions used in setting the standards are not appropriate for all purchasers, then overly stringent standards run the risk of leaving consumers worse off.

Environmental externalities. Economic analysis of environmental policy is based on the idea that the potentially harmful consequences of economic activities on the environment constitute an externality. All environmental policies, at their core, are designed to deal with this externality problem, either by internalizing environmental costs so that polluters will make efficient decisions regarding their consumption of environmental inputs, or else by imposing from the outside a level of environmental pollution that policy-makers believe to be more efficient than that otherwise chosen by firms. If energy-related environmental externalities are not fully addressed by environmental policy—for political or other reasons—the resulting level of energy efficiency will likely be too low. In other words, unless the environmental costs of energy are fully paid by producers and users, the price of energy will be too low and the incentive to use energy efficiently will be inadequate. Pollution control policy in the form of standards or incentive-based instruments such as green taxes or tradable permits are the most direct way to address such environmental externalities.

Innovation and adoption externalities. In addition to the externality associated with pollution, innovation and diffusion are both themselves characterized by externalities. A firm that develops or implements a new technology typically creates *benefits* for others, and hence has an inadequate incentive to increase those benefits by investing in technology. With respect to innovation, the positive externality derives from the public-good nature of new knowledge. While patents and other intellectual property rights institutions try to protect firms' investments in innovation, such protection is inherently imperfect. Hence innovation creates positive externalities in the form of "knowledge spillovers" for other firms, and spillovers of value for the users of the new technology.

In addition, production costs tend to fall as manufacturers gain production experience in a process commonly called "learning-by-doing". If this learning spills over to benefit other manufacturers it can represent an additional externality. In any event, the existence of these innovation and adoption externalities suggests a rationale for public support of R&D *in general*, not for energy-efficient technology in particular. To make an argument particularly for energy-efficient technologies in this regard, one would have to argue that spillovers related to these technologies were somehow greater than for technologies more generally in the economy. For instance, if political or other constraints do not allow for proper pricing of environmental externalities, such as global climate change, then there would tend to be an additional rationale for R&D specifically targeted at environmentally beneficial technologies.

IV. Differing perspectives on the ability of policy to cost-effectively capture potential energy efficiency

Although there is not much disagreement among analysts about the conceptual plausibility of the above market failures, there is significant disagreement about the size of the resulting economic inefficiencies and the ability of practicable policies to eliminate these inefficiencies at acceptable cost. In cases where implementation costs outweigh the gains from corrective government intervention, it will be more efficient not to attempt to overcome particular market failures.

What are the sources of these differing perspectives? More optimistic projections of cost-effective energy efficiency opportunities typically define optimal energy efficiency by minimizing the total purchase and operating costs of an investment, where energy-operating costs are discounted at a rate which may not correspond to the purchaser's point of view.

The problem with this approach is that it does not accurately describe all the issues which can influence energy-efficiency investment decisions. First, the importance of certain factors can vary considerably among purchasers, including the purchaser's discount rate, the investment lifetime, the price of energy, the purchase price, and other costs. For example, it may not make sense for someone who will only rarely use an air conditioner to spend significantly more purchasing an energy-efficient model; they simply may not have adequate opportunity to recoup their investment through energy savings.

In addition, there are typically costs of adoption that are not included in simple cost-effectiveness calculations. It is by no means costless to learn how a technological improvement fits into one's home or firm or to learn about reliable suppliers. Even after basic information about a technology has been disseminated, the purchase price of a new product is only a lower bound on its adoption cost. Another type of "hidden cost" is the possibility that qualitative attributes of new technologies may make them less desirable than existing, less efficient technologies. An obvious example is the difference in hue between florescent and incandescent lighting, and the delay in many florescent lights.

Moreover, most estimates do not account for changes over time in the savings that purchasers might enjoy from an extra investment in energy efficiency, which depends on trends and uncertainties in the prices of energy and conservation technologies. When making irreversible investments that can be delayed, the presence of this uncertainty can lead to a higher investment-hurdle rate. The magnitude of this "option-to-wait" effect depends on project-specific factors, such as the degree of energy-price volatility, the degree of uncertainty in the cost of the investment, and how fast the prices of energy and conservation technologies are changing over time.

Finally, there is evidence that energy savings from higher efficiency levels have routinely been overestimated, partly because projections often are based on highly controlled studies that do not necessarily apply to actual, realized savings in a particular situation. For example, studies have found that actual savings from utility-sponsored programs typically may achieve only 50% to 80% of predicted savings. Another study found that the actual internal rate of return to residential energy conservation investments on insulation was about 10%, which is substantially below typical engineering estimates that the returns for such investments were 50% or more.

Requiring consumers to purchase appliances with a higher level of efficiency based on overly simplistic analysis will, in effect, impose extra costs on consumers. The result will be a higher level of energy efficiency, but decreased economic efficiency because consumers would be forced to bear costs that they had otherwise avoided.

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Pew Center/NCEP 10-50 Workshop

Improving Industrial Energy Efficiency in the U.S.: Technologies and Policies for 2010 to 2050

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I. Introduction

Characterizing industry in the U.S. is difficult since it covers an extremely diverse range of activities. In 2000, industry was responsible for 30% of the greenhouse gas (GHG) emissions in the U.S. and consumed 35% of the country's primary energy. Over half of this energy was used in energy-intensive industries producing commodities such as steel, cement, paper, and aluminum; the remainder was consumed by light manufacturing industries. Economic development patterns are leading to a shift away from these energy-intensive industries toward lighter, higher value-added industries, which will be responsible for more than half of all manufacturing energy use by 2050.

Historically, industrial energy consumption in the U.S. showed an overall decline between 1973 and 1986 when energy prices were relatively high, but has grown annually since then. The U.S. Energy Information Administration projects that energy consumption and GHG emissions for U.S. industry will continue to grow and, extrapolating current reference case growth rates, will double by 2050. However, technologies and policies are available that can reduce this growth considerably.

II. Necessary Technical Advances

Currently many opportunities exist to improve industrial energy efficiency and there is a large potential for future efficiency developments. Improving industrial energy efficiency and reducing energy-related GHG emissions can be accomplished through technological improvements as well as changes in the structure of the overall industrial sector (in reaction to economic and environmental drivers). In addition, further reductions in GHG emissions from industry can be realized through reduction of process-related emissions, fuel switching to lower carbon fuels, and integrated pollution prevention and material efficiency improvement. All of these opportunities are available on the near-term and many will continue to be available in the medium- and long-term.

For a variety of reasons, many of the energy-intensive industries in the U.S. are relatively energy *inefficient* when compared to their counterparts in Europe, Japan, Canada, or to rapidly industrializing countries such as South Korea, suggesting considerable potential for energy efficiency improvement in the *short term*. Recent comparisons and analyses show that some heavy industries in the U.S., such as those that manufacture steel, cement, paper, and some chemicals, use more energy per ton of product produced than many of their international counterparts. Since 1976, the U.S. Department of Energy's Industrial Technologies Program and Industrial Assessment Centers have conducted almost 12,000 energy-efficiency assessments in virtually all industries in the U.S. and have made over 82,000 recommendations for actions to increase energy-efficiency in the facilities audited (Rutgers University, 2003). Audits of individual plants further demonstrate the existence of these opportunities (U.S. DOE, 2003a). Many companies implementing energy management systems also find substantial room for improvement in their operations. Based on these studies we estimate that through adoption of commercially proven cost-effective technologies and measures, most industries currently can reduce their energy intensity by 20% or more (Interlaboratory Working Group, 2000; Martocci, 1996; Phylipsen, 2000; Worrell et al., 1999). Furthermore, many of these existing technologies will positively impact productivity and environmental performance.

For most industrial processes, current efficiency levels are nowhere near thermodynamic optimal levels. This suggests that there will be ample future energy-efficiency improvement opportunities. Technology development and innovation improve the overall performance of industrial technologies and often result in improvements in energy efficiency. Hence, emerging technologies provide further opportunities for energy efficiency improvement beyond currently available technologies. In fact, several studies demonstrate that society will "not run out of technologies", but that investment in technology development and research will provide a steady menu of energy-efficient technologies. For example, a recent report on emerging energy-efficient technologies identified approximately 175 technologies for reducing energy use in a variety of industries that were under development or near commercialization (Martin et al., 2000). U.S. Department of Energy's Industries of the Future program has worked with 10 industrial sectors to identify the most promising technologies and practices to receive further research and development (R&D) funding. Each industry has identified around 100 to 150 technologies or processes in industry-specific R&D portfolios (U.S. DOE, 2003b). Other studies indicate long-term potential energy-efficiency improvements ranging between 30 and 65% in the major industrial sectors, 43% for nitric acid production, 34 to 50% for iron and steel production, and 50 to 70% for paper production (ATLAS, 2003; de Beer, 1998). These analyses show that many technologies will be available in the medium term and development will continue to offer a menu of further technologies in the long term.

Along with the development and deployment of energy-efficient technologies, patterns of energy use and associated GHG emissions change over time as the types of industries and products produced evolve in response to infrastructure development needs and consumer preferences. Studies of material consumption in industrialized societies show increases in consumption of basic industrial materials in the initial development of society to a maximum consumption level, which then remains constant or even declines as infrastructure needs are met, higher value-added products are produced, and material recycling increases (Williams et al., 1987; WRI, 1997). Production of primary steel from iron ore in the U.S., for example, peaked in the 1970s and steel demand is increasingly being met through the production of recycled steel (AISI, various years). This dematerialization will continue and contribute to changes in economic activities. Further potential for material efficiency improvement currently exists which can reduce industrial energy use through product design, product re-use, recycling and material substitution. Integrated analyses of the potential for GHG emissions reduction have shown that a strategy combining energy and material efficiency opportunities will provide a more cost-effective strategy (Gielen, 1995).

Further near-term reductions in GHG emissions, beyond those from improvements in energy and materials efficiency, can be realized through reductions in process-related emissions. Non-energy-related GHGs, including carbon dioxide (CO_2), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6), are emitted during manufacturing of cement, aluminum, semiconductors, adipic acid, nitric acid, magnesium and electrical distribution equipment. Technologies and measures to reduce these process-related emissions are well known and significant progress has been made in some areas to reduce these emissions. In cement manufacturing, 50 percent of the GHG emissions are process related. There is still great potential to reduce CO2 emissions through the use of blended cements. Blended cements replace some of the cement with other less CO2-intensive materials. Blended cements, while customary in virtually all areas of the world, are not typically used in the United States. (Worrell et al., 2001)

Finally, additional reductions in GHG emissions from industrial-related activities in the U.S. can be realized through fuel-switching to low- or no-carbon fuels. The switch in fuels would also allow the introduction of more efficient conversion technologies, such as combined heat-and power production using natural gas. In fact, historic global trends show a movement toward easy-to-use forms of energy, which are often low-carbon fuels (Nakicenovic et al., 1998). Increased use of biomass-derived fuels in the pulp and paper industry has limited the growth of CO_2 emissions, and new technology would allow manufacture of virtually CO_2-free paper when produced in efficient mills.

III. Necessary Policies

The process for identifying, developing, and integrating these myriad technologies and measures for reducing energy use and GHG emissions from industry is an inherently complex and “messy” one (Nakicenovic et al., 2000). Even so, it is important to develop a menu of policy options with the appropriate mix of policies determined by current conditions as well as immediate and longer term goals. Policies to accelerate technological change are key to ensuring that outdated technologies do not get adopted and “locked-in” when more efficient technologies are available. Such policies can also provide incentives to innovators and early adopters, encourage implementation of best practices, and accelerate the realization of potential energy savings. However, such policies will not be sufficiently effective to meet the challenge when implemented in isolation among many other policies. It is essential that an over-arching, climate-friendly policy framework create markets for currently available energy-efficient technologies, and by doing so provides a powerful driver for expanded and accelerated R&D by the private sector.

In the near term, further efforts are needed to ensure that innovative energy-efficient technologies are adopted in the marketplace. Regulations and standards, aimed at eliminating the most wasteful products on the market, can be updated and extended to new products as technologies advance. A recent analysis of the effect of nine appliance standards enacted and updated between 1987 and 2000 found cumulative energy savings of 4.0 Quads and economic savings of $10 billion (Meyers et al., 2002). Market transformation programs that provide incentives for consumers to purchase more energy-efficient equipment and technologies can help in introducing new energy-efficient technologies as well as “push” the market toward more efficient products. Government procurement programs that require purchase of energy-efficient equipment, as well as consumer rebates and tax incentives, are all effective means of moving the market away from inefficient products.

To assure availability of technology options in the long term, research and development (R&D) programs are essential for the fundamental work needed to identify and develop specific energy-efficient and GHG emissions reduction technologies. Both government-sponsored and private sector R&D funding in the U.S. have declined in recent years. Public sector R&D spending saw the most dramatic decline, illustrated by the Department of Energy’s drop in such expenditures from $6.55 billion in 1978 to $1.92 billion in 1997 (PCAST, 1997). Given the significance of energy consumption and energy efficiency (e.g. energy expenditures account for about 8% of GDP in the U.S., energy consumption contributes to considerable environmental problems, and energy consumption is closely linked to national security issues), the President's Committee of Advisors on Science and Technology (PCAST), a panel that consisted mainly of distinguished academics and private sector executives, recommended that the DOE energy efficiency budget should be doubled between FY1998 and FY2003, and estimated that this investment could produce a 40 to 1 return for the nation including reductions in fuel costs of $15-30 billion by 2005 and $30-45 billion by 2010 (PCAST, 1997). State-level R&D efforts, such as those in New York and California, can also make significant progress toward addressing state-specific energy efficiency needs.

Experience in a number of countries around the world using an innovative policy mechanism called Voluntary Agreements has shown that these programs, which push industry to achieve aggressive energy-efficiency targets with support from the government, could be attributed with about 50% of the observed energy-efficiency improvement or emissions reductions (Dowd et al., 2001). For example, in The Netherlands the historical energy intensity improvement rate of about 1% per year was more than doubled during the 10-year period covered by the industrial Voluntary Agreement program (Kerssemeeckers, 2002). These “voluntary” agreements are sometimes an integrated part of a larger national energy policy scheme that includes energy or GHG taxes or additional environmental regulations for those industries that do not sign agreements, providing further incentive and economic savings for those industries that participate.

The most effective means for improving energy efficiency or reducing GHG emissions is through adoption of an integrated long-term policy framework to address these challenges. Countries as diverse as China and the Netherlands have shown that a commitment to improving energy efficiency while allowing for continued economic growth can significantly reduce energy use per unit of production. Similarly, the United Kingdom has recently announced a goal of surpassing its Kyoto Protocol target of reducing emissions of CO_2 by 20 per cent below 1990 levels by 2010, to reduce carbon dioxide emissions by 60% by 2050 (UK DTI, DfT and DEFRA, 2003). A targeted approach is also successful within corporations, as evidenced by companies like BP and DuPont that achieved major reductions in GHG emissions within relative short periods. An integrated policy framework that provides clear direction on long-term goals, while providing market drivers for energy-efficient technology adoption, development and innovation can provide industry with a diverse menu of options to improve its energy and economic performance.

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Hydrogen in Transportation

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Hydrogen as an Energy Carrier: Outlook for 2010, 2030 and 2050

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Introduction: Why consider hydrogen as a future energy carrier?

Globally, direct combustion of fuels for transportation and heating accounts for about two thirds of greenhouse gas (GHG) emissions, a significant fraction of air pollutant emissions and about two thirds of primary energy use. Even with continuing incremental progress in energy technologies; primary energy use, and GHG and air pollutant emissions from fuel use will likely grow over the next century, because of increasing demand, especially in developing countries. To stabilize atmospheric CO_2 concentrations at levels that avoid irreversible climate changes,[1] integrated assessment models suggest that it will be necessary to reduce carbon emissions from fuel combustion several-fold over the next century, as compared to a "business as usual" scenario, even if the electric sector completely switches to non-carbon emitting sources by 2100 (Williams 2002). Air quality remains an issue in many parts of the world. Moreover, fuel supply security is a serious concern, particularly for the transportation sector.

A variety of efficient end-use technologies and alternative fuels have been proposed to help address future energy-related environmental and/or supply security challenges in fuel use. Alternative fuels include reformulated gasoline or diesel; compressed natural gas; methanol; ethanol; synthetic liquids from natural gas, biomass or coal such as Fischer-Tropsch liquids or dimethyl ether (DME); and hydrogen. Recently, hydrogen has received increased attention worldwide, because it offers perhaps the greatest long-term potential to radically reduce several important societal impacts of fuel use at the same time.

Hydrogen can be made from widely available primary energy sources including natural gas, coal, biomass, wastes, solar, wind, hydro, geothermal or nuclear power, enabling a more diverse primary supply for fuels. Hydrogen can be used in fuel cells and internal combustion engines (ICEs)[2] with high conversion efficiency and essentially zero tailpipe emissions of GHGs and air pollutants. If hydrogen is made from renewables, nuclear energy, or fossil sources with capture and sequestration of carbon, it would be possible to produce and use fuels on a global scale with nearly zero full fuel cycle emissions of GHG and greatly reduced emissions of air pollutants.

Most analysts believe that hydrogen will only become viable if public policy more aggressively addresses the societal impacts of fuel use. However, the intriguing possibility has been raised that hydrogen and fuel cells might enable improved energy services and new features, such as clean, quiet, mobile electricity generation, that would make them attractive to consumers, even without policies considering external costs of energy (Burns et al. 2002). Some see hydrogen and fuel cells as "disruptive technologies" that could change how we produce and use energy in profound ways.

Hydrogen also poses the greatest challenges of any alternative fuel: there is an array of technical, economic, infrastructure and societal issues that must be overcome before it could be implemented on a large scale. Technologies for hydrogen production, storage and distribution exist, but need to be adapted for use in an energy system. Building a new hydrogen energy infrastructure would be expensive and involves logistical problems in matching supply and demand during a transition. Hydrogen technologies such as fuel cells, and zero-emission hydrogen production systems are making rapid progress, but technical and cost issues remain before they can become economically competitive with today's vehicle and fuel technologies.

This report examines the current status of hydrogen technologies, possible paths forward and the issues associated with a transition toward large-scale use of hydrogen. It discusses technical milestones, actions and policies that might be needed for successful development of hydrogen energy systems. There are still major uncertainties about the future performance and cost of hydrogen technologies versus competitors, and in the future policy landscape, making it difficult to project future markets over a 50-year time frame. Because of these uncertainties, this report discusses hydrogen transitions in the context of a possible future where externalities begin to receive serious attention and where hydrogen technologies reach their technical and cost goals, both within the next decade or so. A possible timeline for hydrogen energy systems is sketched, and near to mid-term "no-regrets" actions are suggested.

Overview of Hydrogen Technologies: Present Status, Challenges and Policy Implications

Today's Industrial Hydrogen System

Technologies to produce, store and distribute hydrogen for industrial markets are well established. Hydrogen is widely used for a variety of applications such as the refining of crude oil, production of ammonia and methanol, production of semiconductor chips, processing of edible oils, surface treatment of machined metal parts and other chemical uses. The annual worldwide production of hydrogen is about 50 million (metric) tonnes (equivalent to about 2% of global primary energy use), the vast majority (95%) of which is made from fossil fuels and used within large refineries and ammonia and methanol plants. There is also a smaller but rapidly growing merchant hydrogen industry, which makes and supplies about 2.5 million tonnes of hydrogen per year to customers (enough to fuel about 14 million hydrogen cars if they filled up once every 8 days with 4 kilograms of hydrogen each time.) (See Raman.) Hydrogen is delivered in trucks as a high-pressure compressed gas or cryogenic liquid or by gas pipeline (there are more than 1,000 miles of hydrogen pipelines serving large refineries and chemical plants in several locations around the world). The current industrial hydrogen system provides a technical starting point for building a future hydrogen refueling infrastructure, although new engineering (and new or at least updated regulatory regimes) would be needed to adapt industrial hydrogen technologies to an energy system serving mass consumer markets with near zero emissions of GHGs and air pollutants.

Hydrogen Production

Current Status

Hydrogen Production from Hydrocarbons: About 95% of hydrogen today is produced from fossil fuels using high-temperature chemical reactions that convert hydrocarbons to a synthetic gas, which is then processed to make hydrogen. In many areas of the world, including the United States, large-scale natural gas reforming is currently the lowest cost method for hydrogen production. Systems are being developed for small-scale production of hydrogen from natural gas, at a size appropriate for vehicle refueling stations or fueling stationary fuel cells in buildings. Hydrogen could also be produced at large scale by gasification of feedstocks such as coal, heavy oils, biomass, wastes or petroleum coke. In regions with plentiful, low-cost biomass resources, biomass gasification could become an economically attractive method of hydrogen production. Limiting factors are likely to be land availability and competing uses for low-cost biomass feedstocks in the electricity sector.

Fossil Hydrogen and CO_2 Sequestration: When hydrogen is made from fossil fuels, carbon dioxide can be separated, compressed, transported by pipeline and “sequestered” in secure underground storage sites such as deep saline aquifers or depleted oil and gas fields. Carbon capture and sequestration are key enabling technologies for fossil hydrogen as a long-term, low carbon-emitting option. (For example, without carbon sequestration, vehicles using hydrogen from natural gas would offer modest [10-40%] reductions in GHG emissions,[3] compared to advanced ICE vehicles fueled with natural gas, gasoline or diesel [Wang 2002]. With CO_2 sequestration well-to-wheels GHG emissions might be reduced by 80-90%.) Technologies for CO_2 capture, transmission, and sequestration are used for enhanced oil recovery today, and several large-scale demonstrations of CO_2 capture and sequestration are ongoing or planned in the United States and Europe. However, there are still many unanswered scientific and cost questions about long-term storage of carbon dioxide (See companion workshop papers on Carbon Sequestration).

Hydrogen Production via Electrolysis: Water electrolysis is a mature hydrogen production technology, in which electricity is passed through a conducting aqueous electrolyte, "splitting" water into hydrogen and oxygen. Electrolysis is a modular technology that can be used over a wide range of scales from household to large central hydrogen plants serving a large city. Research is ongoing to reduce capital costs and improve efficiencies of electrolysis. The production cost of electrolytic hydrogen strongly depends on the cost of electricity. Today, electrolytic systems are generally competitive with steam reforming of natural gas only where very low cost (1-2 cent/kWh) power is available (Thomas et al. 1998, Ogden 1999, Williams 2002).

Depending on the source of the electricity, the full fuel cycle carbon emissions from electrolytic hydrogen production could range from zero (for hydropower, wind, solar, geothermal or nuclear power) to quite large (for coal-fired power plants without CO_2 sequestration). Off-peak power could be a locally important resource for electrolytic hydrogen production, particularly in areas where low-cost excess hydropower or geothermal power is available. Solar and wind power are potentially huge resources that could produce enough electrolytic hydrogen to satisfy human needs for fuels, with zero emissions of GHG and air pollutants. At large scale, electrolytic hydrogen from intermittent renewable sources is projected to be more costly to produce than hydrogen from fossil fuels, even if future cost goals are reached for wind and solar electricity (Myers et. al 2003), and even when the costs of CO_2 sequestration are added to the fossil hydrogen production cost (Williams 2002). Nuclear electrolytic hydrogen would be high cost as well, unless low-cost off-peak power from a nuclear plant were used. In addition there are issues of weapons proliferation and waste disposal associated with nuclear energy. (See companion workshop paper on nuclear energy.)

Advanced hydrogen production methods using renewable or nuclear energy: Water splitting can also be accomplished through a complex series of coupled chemical reactions driven by heat at 400-900 degrees C from nuclear reactors or solar concentrators. Thermo-chemical water splitting cycles are still undergoing research, and are not as technically mature as hydrogen production systems such as steam reforming, coal or biomass gasification, or water electrolysis, and should be considered a longer-term possibility. Fundamental scientific research is being conducted on a variety of other experimental methods of hydrogen production including direct conversion of sunlight to hydrogen in electrochemical cells, and hydrogen production by biological systems such as algae or bacteria. These methods are far from practical application for commercial hydrogen production.

Summary of Hydrogen Production Costs

How does hydrogen compare in cost to other fuels? In Figure 1, we estimate the delivered cost of hydrogen for several supply options. These include both near-term options (truck delivery of liquid hydrogen, onsite production of hydrogen in small electrolyzers or steam methane reformers) and long-term centralized options (central fossil hydrogen production with and without CO_2 sequestration, nuclear thermo-chemical water splitting and central electrolysis using electricity costing 3 cents per kwh). The delivered cost of hydrogen including production, delivery and refueling stations is approximately \$2-3.5 per kg of hydrogen. (The energy content of 1 kg of hydrogen is about the same as 1 gallon of gasoline, although hydrogen can be used more efficiently.)[4] In the near term, onsite production of hydrogen from natural gas is the most attractive option. In the longer term, zero GHG emission hydrogen supplies will presumably be phased in, but have a higher cost. At large scale, CO_2 sequestration is projected to add relatively little to the delivered cost of hydrogen (Williams 2002, Ogden 2003). A recent assessment of the potential for renewable hydrogen production in the United States found that it was technically feasible to make 10 Quadrillion Btu of hydrogen per year (enough hydrogen for more than 100 million light duty vehicles), with delivered hydrogen costs ranging from \$3-4.5/kg for various renewable sources such as wind-powered electrolysis and biomass gasification (Myers et al. 2003).

Policy Implications

Fossil-derived hydrogen (without CO_2 sequestration) is likely to be the lowest cost hydrogen supply in many places over the next few decades, offering modest societal benefits (e.g. significant reductions in air pollutant emissions and oil use per mile of vehicle travel, but modest reductions in well to wheels GHG emissions per mile as compared to advanced ICE vehicles using conventional fuels [Wang 1999, Weiss et al. 2000, Ogden, Williams and Larson 2004]). Renewable hydrogen could be locally important in the near term, where low-cost renewable resources are available. In the long term, to fully realize hydrogen's benefits, it will be important to widely implement zero-emission hydrogen production systems. As discussed above, each of these options faces significant challenges before it could be implemented on a global scale. Vigorous support for RD&D on zero-GHG emission hydrogen production technologies is needed, even if hydrogen is made from fossil sources such as natural gas in the near term. Many of the enabling technologies (such as gasification, CO_2 sequestration and wind power) have potential applications in the electric sector as well, and are being developed for electric markets.

Hydrogen Storage

Present Status

Unlike gasoline or alcohol fuels, which are easily handled liquids at ambient conditions, hydrogen must be stored as a compressed gas (in high-pressure gas cylinders), as a cryogenic liquid at -253°C (in a special insulated vessel or dewar) or in a hydrogen compound where the hydrogen is easily removed by applying heat (such as a metal hydride). Commercial, large-scale bulk storage of industrial hydrogen is typically done as a compressed gas or a cryogenic liquid. Very large quantities of hydrogen can be stored as a compressed gas in geological formations such as salt caverns or deep saline aquifers

Hydrogen onboard storage systems now under development for vehicles are bulkier, heavier and costlier than those for liquid fuels (like gasoline or alcohols) or compressed natural gas, but are less bulky and heavy than electric batteries. Automotive manufacturers have identified hydrogen storage for light duty vehicles as a key area for RD&D, as none of the existing hydrogen storage options simultaneously satisfy the manufacturers' goals for compactness, weight, cost, vehicle range and ease of refueling. Current hydrogen vehicle demonstrations are focused on compressed gas storage, because of its simplicity. Innovative storage methods such as hydrogen adsorption in advanced metal hydrides, carbon nano-structures and chemical hydrides are being researched, but none are near commercialization.

Challenges and Policy Implications

Support for R&D on hydrogen storage could have a large payoff. Development of a novel hydrogen storage medium that required neither high pressure nor low temperature would not only facilitate use of hydrogen in vehicles, but could reduce hydrogen infrastructure costs and complexity as well. (Over half of the capital cost of a hydrogen refueling infrastructure with pipeline distribution of gas to refueling stations is due to compressors and pressure storage vessels. [Ogden 2003]). Compressed gas storage and refueling are relatively simple technically, and could work in the long term, even without a storage breakthrough, although there is considerable cost and energy use involved in hydrogen fuel distribution compared to liquid hydrocarbon fuels. Also, if large amounts of bulky above-ground compressed hydrogen gas storage were needed, this might require creative use of space at refueling stations. Too early an investment in an extensive compressed gas hydrogen infrastructure might result in "stranded assets" if a breakthrough in hydrogen storage materials occurred later. Over time, incremental infrastructure decisions could take advantage of improvements in hydrogen storage technologies.

Hydrogen Delivery Infrastructure: Hydrogen Transmission, Distribution, Refueling

Present Status

Long-Distance Hydrogen Transmission: The technologies for routine handling and delivery of large quantities of hydrogen have been developed in the chemical industry (see Raman). Liquid hydrogen is delivered by truck or rail over distances of up to several hundred miles. Compressed gas hydrogen pipelines (up to several hundred kilometers in length) are used commercially today to bring hydrogen to large industrial users like refineries. For a large-scale hydrogen energy system, it would probably be less expensive to transport a primary energy source (like natural gas or coal) to a hydrogen plant located at the "city gate," rather than making hydrogen at the gas field or coal mine and piping it to the city. In the long term, transcontinental hydrogen pipelines seem unlikely, unless there were a compelling reason to make hydrogen in a particular location far from demand.

Local Distribution and Refueling: For local distribution of hydrogen from the city gate to users such as refueling stations, compressed gas or liquid hydrogen trucks or high-pressure, small-diameter pipelines analogous to natural gas utility "mains" might be used. The cost of building local distribution pipelines through an urban area is likely to be quite high, on the order of $1 million/mile, depending on the area. A large and geographically dense demand would be required for cost-effective local hydrogen pipelines. This might not occur until 10-25% of the cars in a large urban area used hydrogen.

There are currently about 60 hydrogen refueling station demonstrations worldwide for experimental vehicles, using a variety of approaches, including truck delivery and onsite production from small-scale electrolysis or steam reforming of natural gas.

The cost of building a full-scale hydrogen refueling infrastructure (assuming a large fraction of future vehicles use hydrogen) has been estimated at hundreds to thousands of dollars per vehicle, depending on the level and geographic density of demand and the hydrogen production technology required (Ogden 1999, Mintz et al. 2002, Thomas et al. 1998) Early infrastructure will be more costly per vehicle, because of economies of scale and low density of demand. In the longer term, zero-emission hydrogen supplies are likely to have a higher capital cost per car.

Challenges and policy implications

For implementing a future hydrogen delivery infrastructure, the major challenges are likely to be more economic and logistical than technical. In particular, matching supply and demand during a transition at low cost is a key issue. To address the associated "chicken and egg" problem, coordination between fuel suppliers and fuel users will be needed during infrastructure growth. In addition, government support may be needed to encourage early infrastructure investments, before economies of scale can be realized.

A possible development path for hydrogen infrastructure is sketched below (see also Raman and Nemanich). Initially, when demand for hydrogen energy is small, hydrogen will be delivered by truck from centralized plants, similar to today's merchant hydrogen system. Excess capacity in the merchant hydrogen system could be used for early demonstration projects. Mobile refuelers might be used (a compressed hydrogen gas storage system and dispenser mounted on a small trailer that could be delivered by truck to refueling sites and replenished at a central hydrogen plant). Alternatively, hydrogen could be produced at the end-user site (e.g. a refueling station or building) by small-scale electrolysis or steam reforming of natural gas. Onsite production avoids the cost of hydrogen distribution, and allows supply to grow incrementally with demand. One of the benefits of central production is that zero-emission sources can be more easily used and control of emissions including CO_2 is easier to accomplish. (It might also be possible to make hydrogen at refueling stations, for example, from renewable electricity, such as off-peak hydropower.) As hydrogen demand increases, pipeline distribution could be considered for large, geographically dense demands. Local distribution pipelines are most likely to make economic sense where a large demand is located near an existing supply, or in large cities with geographically dense demand and a high fraction of hydrogen vehicles (probably at least 10% [Ogden 1999]).

The existing energy infrastructure could strongly influence how hydrogen supply evolves in the near term. In the long term, some sites used for energy infrastructure today might remain in use for hydrogen systems, but new development might also be required, and new fuel delivery locations to allow refueling at home or at work. Infrastructure considerations might be different for developing countries, where relatively little fuel supply infrastructure currently exists.

Hydrogen End-Use Technologies

Present Status

Hydrogen Use in Transportation: Hydrogen vehicles are undergoing rapid progress. Experimental fuel cell vehicles have been developed by most automotive manufacturers, and are being tested in small fleet trials of buses and light duty vehicles. However, current automotive fuel cell costs are still perhaps 30-100 times higher than ICEs that cost perhaps $35-45/kW. Further, reliability and durability of fuel cells needs to be improved several-fold. The U.S. government's Freedom Car program with industry has established goals for fuel cells, hydrogen storage and auxiliaries (see Ford Motor Company paper). In the near to mid term, hydrogen internal combustion engines could offer a near-zero GHG emission technology,[5] with lower cost than fuel cells, and high efficiency when used in a hybrid configuration. Hybrid technology development is relevant to future prospects for fuel cell vehicles, because many of the electric drive technologies are similar.

Hydrogen for Heat and Power in Buildings: Although much of the attention has been on hydrogen vehicles, hydrogen might find earlier applications in providing heat and power for buildings, where cost goals are less daunting than for vehicles. Fuel cell cogeneration systems using reformed natural gas are being developed to provide heat and power in buildings. Several hundred natural gas fueled fuel cell cogeneration systems have been installed worldwide. There is growing interest in the "energy station" concept, where natural gas is reformed to power a fuel cell providing building energy plus hydrogen for vehicles.

Early Niche Applications: It has been proposed that hydrogen might be used first in heavy vehicles, including ships and locomotives that currently rely on heavily polluting diesel engines (Farrell et al. 2004). Hydrogen fuel cells might be used in applications where battery electric power trains are used today, and zero air pollutant emissions are required (e.g. vehicles used indoors or mine vehicles). Other early niches for fuel cells might include use as zero-emission mobile auxiliary power units (for auxiliary electrical loads on idling vehicles or at work sites, military "backpack" power, etc.) and as battery replacements (e.g. in laptop computers, power tools).

Challenges and Policy Implications

For hydrogen vehicles to compete in automotive markets they will have to offer the customer comparable or better performance at a similar cost to competing vehicles. Or they must offer societal benefits that are accounted for in policies that help to close the gap between private and public costs/preferences for the vehicles. Incentives would likely be needed to make up any difference in costs, until mass production brought hydrogen vehicles to a competitive level. Clearly, continued RD&D on hydrogen vehicle and fuel cell technologies is key to the success of hydrogen in transportation. Initially, use of hydrogen in heavy vehicles and/or fleet vehicles may be preferred. Demonstrations of hydrogen vehicle technologies over the next decade or so should provide answers to some of these technical and cost questions. Because of the need for coordination between fuel suppliers, auto manufacturers and end-users, public/private partnerships among stakeholders will be needed.

The business case for hydrogen depends on how society values external costs of energy. A "wild card" is the possibility that hydrogen and fuel cells might enable new products and services that would create significant market pull even without considering societal benefits (Burns et al, 2002, Kurani et al. 2004).

Hydrogen Safety

Safety is an assumed precondition for hydrogen energy use by consumers. Hydrogen has been used safely in industrial settings for many decades, and there are efforts underway worldwide to extend this knowledge to general use of hydrogen as a fuel. To this end, it will be important to develop appropriate safety procedures and codes and standards for hydrogen use in energy applications. (See Ringland et al. 1994, Ford Motor Company 1997, Linney and Hansel 1996 for reviews of safety issues for use of hydrogen as a vehicle fuel.) The United States Department of Energy and the National Hydrogen Association are involved in developing codes and standards (USDOE Hydrogen Program website).

Resource Issues for a Hydrogen Economy: Where will hydrogen come from?

A major long-term question for hydrogen is the primary resource used for supply.

Natural gas is widely seen as a transitional source for hydrogen production in the United States over the next few decades, in terms of low cost and low emissions. Several studies have estimated a modest wells-to-wheels GHG benefit in using hydrogen from natural gas in advanced hydrogen vehicles, compared to using liquid fossil fuels in improved ICE hybrid vehicles. (Wang 1999, Weiss et al. 2000, Wang 2002, GM et al. 2001) Moreover, there would be reduced emissions of air pollutants and reduced oil use (although greatly expanded use of natural gas in the United States might come from imports, bringing its own security issues). It might be possible to develop hydrogen end-use technologies (for vehicles and buildings) and bring them to technical readiness over the next few decades, fueled with hydrogen from natural gas, while achieving a reduction in the societal impacts of energy, as compared to what might be achieved with advanced ICE vehicles. The impact on U.S. natural gas supply of making hydrogen for the next decade or so would be relatively small - even under the most optimistic hydrogen demand scenarios, natural gas use would be increased only a few percent by 2025 (Ogden 2004).

Beyond a few decades, in order to realize the low-carbon benefits of hydrogen technologies it would be necessary to change from natural gas without CO_2 sequestration to hydrogen supplies with nearly zero GHG emissions. There is a debate about whether using natural gas to make hydrogen in small reformers for the next few decades would impede a later switch to lower-carbon sources, or would constitute a bridge, allowing development of end-use systems using low-cost hydrogen (Thomas 2003). Promising long-term options that have the potential to reach both low-cost and zero or nearly zero carbon emissions include fossil hydrogen production with CO_2 sequestration, renewable hydrogen (from biomass gasification or possibly wind-powered electrolysis), and hydrogen from off-peak power based on carbon-free electricity. There are ample resources for hydrogen production in the United States, and in most areas of the world. In Table 1, we summarize the primary energy requirements to fuel 100 million hydrogen vehicles (about half the number of light duty vehicles in the United States today), assuming these vehicles are 2 to 3 times as efficient as today's 20 to 30 mile per gallon gasoline light duty vehicles (or 40-60 mpg equivalent).[6] There are clearly many resources that could contribute to hydrogen production in the United States, including renewable resources (Myers 2003).

There are likely to be many solutions for hydrogen supply depending on the level of demand, resource availability, geographic factors, and progress in hydrogen technologies. In the long term, there will be a mix of primary resources for hydrogen supply and hydrogen distribution modes. The mix will probably change as demand grows, and as the cost and availability of primary resources change over time. Depending on the region, different primary resources might be used to make hydrogen. Where external costs of energy are highly valued, this will tend to favor nearly zero GHG emission hydrogen options. Hydrogen will develop first in regions where the case seems compelling on a policy/societal or economic basis; for example in large cities with air pollution problems[7] or island nations with high imported fuel costs (such as Iceland).

Long-term visions of the hydrogen economy, transition paths, and a timeline

Long term visions

Alternative long-term visions of a hydrogen economy have been articulated based on large-scale use of renewables, fossil energy sources (with carbon sequestration) or nuclear energy. These visions share the goal of a zero-GHG emission, more secure fuel supply system using widely available resources. Challenges face each of these zero-emission hydrogen pathways

- For hydrogen from renewables, the issue is primarily cost rather than technical feasibility. Electrolyzers using solar,wind, hydro or geothermal power, and biomass gasification systems could be built today using commercial or near-commercial technology, but, generally, in the United States, delivered hydrogen costs would be higher than for the near-term supply options like steam reforming of natural gas (See Figure 1). For biomass hydrogen the limiting factors might be land availability and competing uses for low-cost biomass feedstocks in the electricity sector.

- Nuclear electrolytic hydrogen suffers from high cost, unless low-cost off-peak power were used. Water splitting systems powered by nuclear heat are still in the laboratory stage, face a number of technical issues, and are less technically mature than renewable or fossil hydrogen systems. Nuclear hydrogen would have the same societal issues as nuclear energy (see companion papers in this workshop on nuclear energy).

- Fossil hydrogen with CO_2 capture and sequestration holds the promise of nearly zero emissions and a relatively low hydrogen production cost, assuming that nearby suitable CO_2 disposal sites are available, and that hydrogen is produced at large scale. (It is not economically feasible to collect CO_2 from small hydrogen production systems such as fueling stations or buildings with onsite reformers.) Much remains unknown about the potential environmental impacts and feasibility of this concept. (See companion workshop papers on geological sequestration.)

In the long term, a hydrogen energy system would use a variety of zero emission supply pathways, depending on regional resources, technical progress, economics, and policies that might favor one resource over another. Hydrogen would be distributed to users by pipeline or truck depending on the level and density of demand (or perhaps via some new method, if there is a breakthrough in hydrogen storage), or produced onsite. There might still be multiple fuels (as today) for different applications (see Greene). Unlike the current transportation fuels, hydrogen might be produced from regionally available primary sources, and the production of fuels, electricity and chemicals could become more closely coupled. A future hydrogen energy supply system will be interdependent with other parts of the energy system. It is important to understand how hydrogen might fit, especially its interactions with the electricity and natural gas systems.

A Timeline for Transition

Setting a precise timeline for a transition to hydrogen is complicated by large uncertainties in projecting technological progress, policies, and future hydrogen markets, and by the site specific nature of hydrogen transitions.[8]To deal with these uncertainties, we set forth a possible scenario for introduction of hydrogen into the energy system.[9] The author first describes a context (in terms of policy, technology and economics), where hydrogen might come into wide use over the next 50 years. The author assumes a high level of societal willingness to address external impacts of energy through policy, and technical and economic success for hydrogen technologies. Absent such a convergence of both political will and technological progress, it is much less likely that hydrogen will play a major role as a future energy carrier. The author then sketches a possible evolution for a hydrogen energy system over the next 50 years within this context, considering likely hydrogen markets, production sources, and delivery infrastructure, and assuming certain technical goals are met. This timeline is summarized in Table 2.

Assumed Potential Scenario for Hydrogen

Policy Context (General):
There is growing will to address climate change issues, and in the 2010 to 2030 timeframe, policies will be enacted at the regional and national level to regulate CO_2 emissions. Air pollution regulations will become increasingly strict in urban areas around the world. Security of energy supply will become an increasingly difficult issue, especially for the transportation sector. Energy policy in the United States will be guided by a continuing debate about the best way to achieve societal goals related to energy, environment and security. Policies to address GHG emissions, air pollutant emissions and national security will send a consistent, strong signal to consumers, vehicle manufacturers, and energy producers to encourage use of cleaner domestic fuels. Beyond 2030, international agreements will be in place to address GHG reductions, including carbon taxes or a carbon cap and trade system. GHG emissions and air pollutants will be strongly regulated in most parts of the world, including developing countries.

Policy Context (Hydrogen specific):
Over the next 10-20 years, vigorous government-supported RD&D programs on hydrogen and fuel cell technologies will be pursued in the United States, the European Union, and Japan, including local and regional demonstration projects, where national and local governments will act as early adopters of hydrogen and fuel cell technologies. Demonstrations of fuel cell buses will also occur in developing countries. Public/private partnerships will be a key aspect of the demonstrations. Policies to implement hydrogen will be enacted in island countries, and in urban areas with high air pollution

emissions. Codes and standards for hydrogen will be established and harmonized throughout the world. Where appropriate, incentives may be put in place to support nascent hydrogen and fuel cell industries, including financial incentives for hydrogen vehicles and hydrogen fuel suppliers to reach commercial viability. Beyond 2030, national policies on hydrogen will be in place, including regulations to facilitate hydrogen infrastructure building.

Technology context: A range of hydrogen technologies will be tested and evaluated over the next 15 years. For hydrogen to go forward, a number of hurdles must be passed. The author makes the following assumptions: Hydrogen and fuel cells meet technical and cost goals for a variety of applications. A decision is made in the 2015-2020 timeframe to commercialize hydrogen fuel cell vehicles in light duty markets. Onsite hydrogen supply systems based on small-scale natural gas reformers and electrolyzers are commercialized. Enabling technologies for zero-emission hydrogen such as wind power, gasification technologies, and CO_2 sequestration appear in the electricity sector. Beyond 2030, there are further advances in zero emission hydrogen production technologies, and in hydrogen storage. Beyond 2050, a variety of low-cost, zero-carbon hydrogen production, storage and delivery technologies are available. Within the policy context described above, there is a business case for hydrogen and fuel cell technologies, when externalities are considered, leading to commercialization in the 2010-2030 timeframe, and profitable self-sustaining companies beyond this.

Development of a hydrogen energy system

Table 2 sketches a possible evolution for hydrogen markets and infrastructure over time. Beginning with today's chemical markets, hydrogen moves through a succession of niche applications, followed by heavy vehicles, bus and light duty fleet vehicle demonstrations, culminating with introduction into general transportation markets in 2015-2020. In parallel, fuel cell technologies are successful in distributed electric generation markets, providing heat and power in buildings. Over the next decade or so, hydrogen use begins in cities with poor air quality or other locations such as islands with multiple drivers for zero emission technologies and domestic fuels. Hydrogen infrastructure builds on the existing energy system at first, with distribution to early small demands by truck or mobile refueler, followed by onsite production and central production with pipeline distribution. There is a strong trend toward zero-emission supplies of hydrogen sources by 2030, as technologies (such as wind) move from the electric sector to hydrogen production. Between 2030 and 2050, hydrogen captures a growing fraction of vehicle markets, and is distributed to buildings. Regional distribution networks including hydrogen pipelines in cities are developed. Beyond 2050, there is general use of hydrogen in the energy sector, and a large suite of zero-carbon supplies and end-use options.

A No-Regrets Action Agenda

To set out a 50-year action agenda for hydrogen is immensely complicated by the uncertainties. The following "no regrets" actions with regard to hydrogen might be pursued over the next decade or so.

Hydrogen-specific actions over the next decade

- Strong support of RD&D on hydrogen technologies, especially fuel cells, zero-emission hydrogen production (including hydrogen from renewables and research on carbon sequestration) and hydrogen storage.

- Public/private partnerships that bring all the stakeholders together for demonstration of hydrogen technologies. The California Fuel Cell Partnership, the U.S. Department of Energy's FreedomCAR hydrogen program, Icelandic New Energy Ltd. , the European Union's CUTE project, and the United National Development Program demonstrations of fuel cell buses are examples of such efforts. Other regional public/private partnerships are under development worldwide.

- Federal and state governments play a role as early adopters of hydrogen technologies. This could involve demonstration of hydrogen technologies in government buildings and vehicle fleets over the next 5-10 years.

- Establishment of codes and standards for safe hydrogen operation in energy applications. Thus far, national and international standards organizations, industry and professional societies have been developing standards with support from the United States and other governments. The need for harmonized hydrogen codes and standards has been highlighted in the National Hydrogen Roadmap (2002) and in the recent National Academy study of the hydrogen economy (NAE 2004).

- Analysis to better understand the external costs of energy and role of hydrogen in the future energy system. As noted above, not all pathways for hydrogen production and use have the same full fuel cycle emissions of greenhouse gases and air pollutants, the same availability of primary resources or the same implications for security. There is a need for continued analysis and societal debate to understand alternatives for reducing societal impacts of energy, and hydrogen's role. (Or as David Greene posed this question, "Is hydrogen THE answer?") This point is emphasized in a recent report by the National Academy of Engineering on the Hydrogen Economy (NAE

2004), which suggested development of a systems analysis effort to understand the implications of hydrogen.

General Actions over the next 10-20 years.

- Development of a consistent national energy policy to address societal problems of climate change, air pollution and national security. This includes action on near-term technologies that could help address these problems now (such as energy efficiency and hybrid vehicles), and simultaneously developing hydrogen and other longer-term technologies that will be needed for deep cuts in carbon emissions.

- RD&D on efficient vehicle technologies with applications in a wide range of advanced vehicles (including hydrogen vehicles). These include electric drive train components being developed for hybrid vehicles, and advanced lightweight materials for vehicles.

- RD&D on clean energy technologies with applications in both electricity and hydrogen production. These include wind, solar, gasification technologies, CO_2 sequestration, and biomass energy.

How soon could hydrogen make a major difference in environmental and supply problems?

Even under a scenario of technical success, and strong policy, it will probably be 10-15 years before hydrogen energy technologies start to enter mass markets such as light duty vehicles. Given the time needed to bring hydrogen technologies to commercialization and the long time constants inherent in changing the energy system, most analysts do not see a major role for hydrogen in reducing emissions or oil use on a global scale for several decades. (Local benefits might be felt before this, if hydrogen is used in fleet vehicles in cities, for example.) Beyond 2025, most analysts agree that there is the possibility that use of hydrogen could make a large impact on reducing emissions (NAE 2004). In the mean time, as discussed in David Greene's contributing paper, many other effective approaches (such as higher efficiency vehicles) should be pursued both to address the energy-related problems in the near-term and to drive a long-term shift towards low-carbon energy carriers such as hydrogen. Implementing policies to encourage energy efficiency is not in competition with conducting RD&D on hydrogen: a comprehensive approach should include both near-term and long-term strategies. In fact, promoting energy efficient technologies is synergistic with long term use of hydrogen.

Hydrogen is potentially very important for our nation's energy future.[10] Hydrogen is one of the few widely available, long-term fuel options for simultaneously addressing energy security and environmental quality (including both deep reductions of greenhouse gases and pollutants).[11] Use of hydrogen could transform the ways we produce and use energy. But is future large-scale use of hydrogen a foregone conclusion? Although the potential is tremendous, in the author's view, it is still too early to tell exactly how large hydrogen's role will become over the next 50 years. While a large scale hydrogen economy by 2050 cannot be considered inevitable at this point, a vigorous program of RD&D on hydrogen can be considered a prudent insurance policy against the need to begin radical decarbonization of the fuel sector within a few decades, while simultaneously addressing energy security and pollution problems. Given the promise of hydrogen, the long lead time in accomplishing transitions in the energy system, and the challenges posed by hydrogen, it is important to provide significant support now, so that hydrogen technologies and strategies will be ready when needed.

Table 1. Primary Resources To Make H_2 For 100 Million Light Duty Vehicles in the US, Assuming H_2 Vehicles are 2-3 times as Efficient as Today's 20-30 mpg Gasoline Light Duty Vehicles (40-60 mpg equivalent).[12]

- **Natural Gas:**
  - Current U.S. NG use = 22 EJ/y
  - Projected NG use to make H_2 for 100 million light duty vehicles, if H_2 is made at 80% conversion efficiency
    = 3.8-5.7 EJ/y **(17-26% of total NG use today)**
- **Coal:**
  - Current U.S. coal use = 20 EJ/y
  - Projected coal use for 100 million light duty vehicles, if H_2 is made at 65% conversion eff. = 4.7-7.0 EJ/y **(23-35% of total coal use today)**
- **Biomass:**
  - Current cropland = 1.7 million km^2;
    rangeland + pasture = 2.25 million km^2;
  - biomass production = 15 dry tonnes/y/hectare; 1 dry tonne = 18 GJ;
  - Land for biomass for H_2 (at 60% biomass _ H_2 conv. Eff.)
    = 0.19-0.28 million km^2 **(8-13% of current range and pastureland)**
- **Wind:**
  - U.S. wind power potential > 10,000 billion kWh, from resources > class 3.
  - At 75% electrolysis efficiency, **11-17% of good to excellent wind resources** would be needed for H_2
- **Off-peak power used in 75% efficient electrolyzers:**
  35-53% of total U.S. installed electric capacity, used 12 hours per day

1 EJ = 1 Exajloule = 10^{18} Joules (the U.S. uses about 100 EJ/year of primary energy)

These are values that would be needed if all the hydrogen is made from one resource only.

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[1] This is often discussed as 450-550 parts per million CO_2 concentration in the atmosphere. (Wigley et al. 1996)

[2] Hydrogen can be used in internal combustion engine vehicles with high efficiency, zero emissions of greenhouse gases and low air pollutant emissions. When hydrogen is burned in air the only air pollutant is NO_x, which can be controlled to low levels. Hydrogen ICE hybid electric vehicles (ICE/HEVs) can be almost as efficient as hydrogen fuel cells. Efficiency of a hydrogen ICE/HEVis typically 80% that of a comparable hydrogen FCV (Thomas et al. 1998).

[3] Well to wheels or "full fuel cycle" emissions refer to all the emissions involved in producing and using a fuel including: primary feedstock extraction, transport of the feedstock to a fuel production plant, fuel production, storage and distribution of fuel, and use of the fuel (for example, in a vehicle). For an excellent description of well to wheels emissions see Wang (1999)

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[4] Hydrogen can be used with 2-3 times the efficiency of today's gasoline vehicles in fuel cell vehicles (see endnote vi below). Even though hydrogen is more costly than gasoline ($2-3.5/kg delivered), it might be used with similar fuel costs per mile to today's vehicles.

[5] As with any hydrogen end-use technology, the degree to which H_2 ICEs will be "zero-emission" on a well to wheels basis will largely depend on the source of the primary energy used to make the hydrogen.

[6] Efficiencies for hydrogen vehicles as compared to internal combustion engine vehicles have been modeled in (Thomas et al. 1998, Weiss et al. 2000, GM et al. 2001). These studies indicate that the energy efficiency of a hydrogen fuel cell vehicle might be 2-3 times that of today's gasoline vehicles, or about 40-60 miles per gallon equivalent on an energy basis. Some studies (Thomas et al. 1998, Weiss et al. 2000) have projected even higher fuel economies for advanced lightweight hydrogen vehicles.

[7] There is a question whether local air pollution concerns will drive a push towards hydrogen or whether evolution of conventional pollution control vehicle technologies (e.g. SULEVs) will be sufficient to address such concerns. In particular, there is a question whether Diesel hybrid will reach SULEV standards and high fuel economy to give a similar combination of environmental benefits as H_2 FCVs

[8] Despite rapid progress and promising results, there is still uncertainty in the future cost and performance of hydrogen technologies (How soon and how well will hydrogen vehicles meet their goals? How much will hydrogen from zero emission sources cost?) and in understanding possible new markets for hydrogen driven by new products or services like mobile electricity.

It is uncertain how soon and where policies will be enacted to address the external costs of energy (not only greenhouse gases but also air pollutants and national security), and what this will mean for hydrogen demand. Integrated assessment models suggest that within a few decades we will need to start dramatically reducing GHG emissions from the energy supply. There is a growing body of analysis on the lowest cost ways to do this. However, the best timing for radical decarbonization of the fuels sector and the potential for energy efficiency and alternative fuels to contribute are still unknown. The fact that hydrogen offers strong multiple benefits complicates the question of timing, as GHG reduction is not the only driver for hydrogen.

Depending on the location, a hydrogen transition will happen in different ways and at different times There is no one solution for designing a hydrogen infrastructure or a hydrogen transition that is preferred under all conditions. The most attractive option in terms of cost and/or emissions depends on a complex set of factors related to the size and type of demand, technology progress, the availability of resources for hydrogen production, and existing infrastructure.

The current lack of knowledge about future demand and markets for hydrogen energy makes it difficult to make projections about the timing for using various hydrogen supply options. Future hydrogen demand scenarios that have appeared in recent years vary widely, projecting between 1% and 100% hydrogen use in transportation by 2050 (EIA 2003, Mintz 2003).

[9] Of course, the scenario described in Table 2 is only one possible future. The author does not consider futures where hydrogen technologies are unsuccessful as hydrogen energy use would be minimal in this case, or only partly successful (see Greene). Nor does the author consider futures where society does not muster the will to address external impacts of energy, although it is conceivable that market pull for new products might lead to large markets for hydrogen even in that situation.

[10] The author's views are similar to those voiced by the National Academy of Engineering about the potential importance of hydrogen to the nation's energy future (NAE 2004).

[11] Near-term technologies (such as hybrid internal combustion engine vehicles using conventional fuels) could provide some level of these benefits sooner and at a lower cost, while hydrogen technologies are being developed. But ultimately, greater emissions reductions from fuels use will likely be needed to achieve societal goals. The long-term contenders for deep emissions reductions in the transport sector are vehicles using renewable biofuels, electric batteries or and hydrogen. Biofuels could potentially give net zero carbon emissions well to wheels (assuming that fossil fuels now used in cultivation, fertilizers or harvesting were replaced with renewable substitutes), but availability of resources, land-use constraints and environmental concerns might limit their use on a global scale. Battery-powered electric vehicles using renewable electricity would offer similar environmental advantages to hydrogen vehicles, but battery costs, recharging time, and range are issues.

[12] NG, Coal, Biomass energy use is from the EIA Annual Energy Outlook. Wind potential is from Myers et al. 2003. H_2 use is calculated for this paper.

Table 2. Context for hydrogen transition, and possible timeline for a hydrogen transition

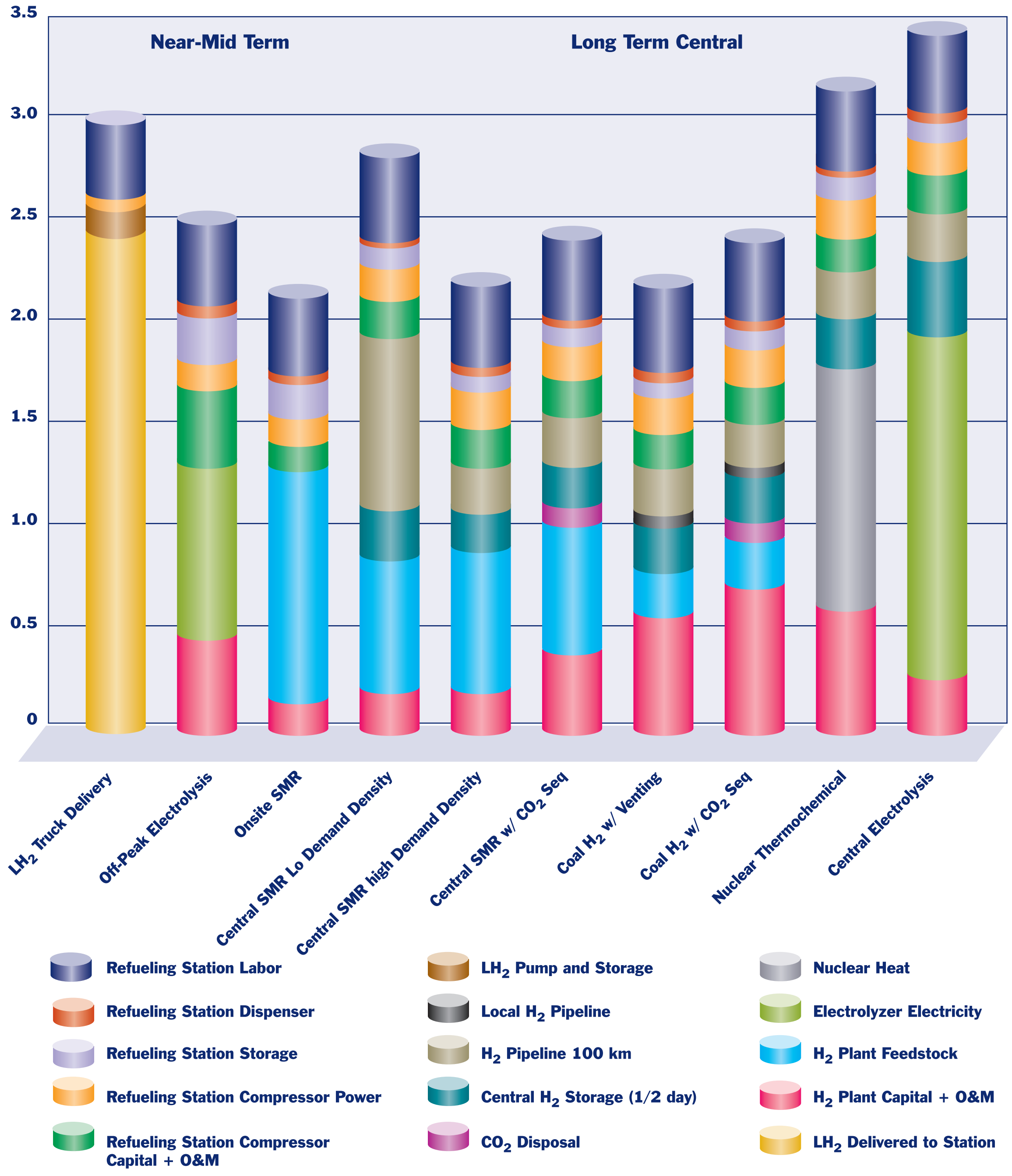
CONTEXT FOR TRANSITION			
	2010-2030	**2030-2050**	**>2050**
POLICY CONTEXT **General**	**GHG Emissions Policy** U.S. National Debate ➠ State and Regional Policy ➠ National Policy **Air pollution regulation, increasingly stringent, zero-emission technologies** State and Regional Policies ➠ National Policy **International Regulations on GHG in several -countries** **National energy security concerns ➠ Policies encouraging domestic fuels** **Consistent energy policy including RD&D on key technologies for energy future** RD&D on range of energy technologies including H2 and enabling technologies like CO_2 seq, wind power **Ongoing debate: which energy alternatives best achieve societal goals**	Increased regulation of GHG worldwide; Broader International agreements on GHG reductions, carbon taxes or cap and trade; Developing country regulations on GHG and pollution; National security concerns encourage use of diverse, secure primary supplies	Regulations on GHG, air pollutants in place worldwide; National security concerns remain important
H_2 specific	Vigorous RD&D programs on H_2 and FC technologies in U.S., EU, Japan; Local and Regional H_2 demonstration projects; Federal and state government early adopter fleets and buildings use H_2. Regional policies to implement hydrogen in urban areas and island countries (Iceland); Public/private partnerships facilitate cooperation between stakeholders; H_2 codes and standards established by 2010; Support nascent high tech H_2 and FC industries; Financial incentives for H_2 vehicles and H2 fuel suppliers to bring to commercial viability; Tax incentives for H_2 fuel.	National policies to use H_2	
TECHNOLOGY CONTEXT	H_2 fuel cells meet durability and performance goals ➠ H_2 FCs meet cost goals Hybrid electric vehicles provide basis for FCV developments H_2 storage goals met for vehicles with incremental improvements Small-scale reformers and electrolyzers successfully commercialized Geological CO_2 sequestration successfully demonstrated Wind power costs reduction	Advanced renewable, fossil w/CO2 seq. and/or nuclear H_2 production option successful; Advanced onboard H_2 storage systems using metal hydrides or lower energy use liquefaction	Variety of efficient, low cost H_2 production, storage delivery technologies available
BUSINESS CONTEXT	H_2 end-use technologies are proved viable and move to commercialization; low- cost, zero emission production technology proves viable; establish coordination among fuel suppliers, vehicles suppliers and users, and governments; H_2 and fuel cells enable new products and services	H_2 and FC businesses self-sustaining	H_2 and FC businesses include well established players in energy field.

MARKETS AND INFRASTRUCTURE DURING TRANSITION

	2010-2030	2030-2050	>2050
H_2 MARKETS Industrial Vehicles Buildings/ Sta. Power	Oil Refining; Chemical Aerospace and military; Niche Electric vehicles; Battery replacement Demonstration Fleets Controlled small fleets ➠ Larger fleets ➠ General vehicle intro (2005-2009) (2009-2015) (market intro 2015-2020) Heavy vehicles (buses, ships) Fuel Cell Cogeneration, possibly with hydrogen co-production	Centrally refueled fleets and public use in automobiles; H2 FCVs capture significant fraction of light duty vehicle market Hydrogen distribution to buildings/commercial/industrial sector?	General use of H2 in energy sector
Production/ Primary Supply	Excess capacity existing H2 infrastructure Steam reforming of natural gas; Partial oxidation of oil; coal gasification; electrolysis; CO2 sequestration demos; Renewable H2 demos;	Fossil with CO2 sequestration; electrolysis powered by zero emission electricity; Biomass gasification Adv. renewable demos Adv. nuclear demos	Fossil with CO2 sequestration; electrolysis powered by zero emission electricity; Biomass gasification; advanced renewable or nuclear
Delivery Infrastructure	Delivery by truck; Mobile refuelers; ➠ onsite production via steam reforming or electrolysis ➠ Pipelines; Infrastructure design site specific; progression from truck delivery to onsite production to central production to use of renewable sources.	Development of regional networks of hydrogen fueling systems, including pipelines in some cities; interaction with electricity system begins; developing country applications	National networks for hydrogen energy; New paradigm for energy production and use; H2 integrated with rest of energy system
Where Will H_2 Be Used?	Local and Regional H2 demonstration projects ➠ small networks in a few cities	Citywide or regional networks; island H_2 systems	National network in large countries like US and in developing countries

Delivered Cost of H_2 ($/kg H2)

$1/gallon gasoline - $1/kg



Climate Change Policy for Transportation While Waiting for H_2

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The vision of a global transportation system powered by hydrogen offers the promise of clean, efficient and sustainable energy for the world's transportation systems, and the possibility of a once-and-for-all solution for transportation's contribution to climate change. But before we decide to place all our bets on the transition from fossil fuels to hydrogen, we should answer three questions.

1. Is hydrogen THE answer to transportation's problems of energy security and greenhouse gas emissions?
2. Is it wise to do little or nothing while we wait for the coming of hydrogen?
3. Will the hydrogen transition just "happen" or must we implement strong policies?

These questions are neither facetious nor trivial. In attempting to answer them, it should become clear that responsible climate and energy policies require much more than a single-minded focus on hydrogen research and development (R&D).

Is hydrogen THE answer for transportation?

It may well be. Using hydrogen as an energy carrier (whether in fuel cells or internal combustion engines) produces very little pollution. Teamed up with electricity, hydrogen could make energy end use virtually pollution free. In addition, hydrogen can be produced from a great many energy sources, including fossil fuels, renewable energy and nuclear energy. Hydrogen could be a flexible and robust energy carrier not tied to depletable fossil resources. However, the cheapest means of producing hydrogen today is from fossil fuels. If hydrogen is produced from fossil fuels, the carbon dioxide generated must be captured and sequestered for there to be significant reductions in greenhouse gas (GHG) emissions versus conventional transportation fuels used with advanced vehicle technologies (e.g., hybrid or diesel powerplants). Carbon sequestration technologies hold a great deal of promise but still face unresolved questions with respect to cost, durability and acceptability.

As a fuel for transportation vehicles, hydrogen faces many technical challenges. Because hydrogen is the smallest and lightest element and a gas under ambient conditions, it is difficult to store in practical quantities for mobile applications. And fuel cells, the key to most envisioned applications for hydrogen, are still an order of magnitude, or more, more expensive than competing conventional technologies. Enormous progress has been made over the past two decades, and it continues to be made rapidly made today. But there is still a long way to go.

What if hydrogen technology does not turn out to be superior to the other alternatives? The possibility must be considered not only because of the challenges facing hydrogen technologies today, but also because the alternatives, especially conventional technologies, are moving targets. Modern internal combustion engine vehicles can be made clean enough to meet California's near-zero emission PZEV (partial zero emission vehicle) standards at a reasonable price. And gasoline- or diesel-electric hybrid vehicles with the potential to increase fuel economy by 50-100% have been shown to offer equal or better GHG performance compared to hydrogen fuel cell vehicles, if the hydrogen is produced from natural gas (the most economical method today) and the carbon is not sequestered. Conventional technology is not only a moving target, but responds and adapts to challenges.

It also seems likely that that hydrogen will succeed in some transportation applications but not in others. For long distance commercial air travel energy density is critical due to the importance of range. Today, it is difficult to see how hydrogen could compete with liquid hydrocarbon fuels without an unforeseen breakthrough in hydrogen storage or a fundamental change in propulsion technology. Can fuel cells or hydrogen internal combustion engines compete successfully against efficient and economical large diesel engines in heavy trucks, locomotives or ships? Light-duty vehicles, the prime target for mobile fuel cells, are the largest mode of transportation but still account for only 55% of transportation's GHG emissions. And if hydrogen is only partly successful in displacing liquid hydrocarbon fuels in transportation, should we not have an effective mitigation strategy for the remaining uses?

The situation we face is illustrated graphically in a simplified way in Figure 1 (competition from other technologies is not represented, nor is the possibility that hydrogen may succeed in only some transportation applications). The key uncertainties are represented by the nodes on a decision tree. Following the lowest branch, if we cannot sequester carbon and we cannot produce it inexpensively from renewable energy, then we cannot achieve significant GHG benefits. To achieve major reductions in transportation's GHG emissions by 2050, we must have carbon sequestration or inexpensive production of hydrogen from renewable energy, or both. And we must have inexpensive fuel cells and much improved hydrogen storage. In a true decision tree, probabilities would be assigned to each decision point. Of course, the probabilities are unknown, but if we assigned a 50/50 chance to each decision point, the probability that hydrogen would eventually significantly reduce transportation GHG emissions would be less than 1 in 5. Even if we decided that 75/25 was a more accurate description of our chances at each decision point, the odds of hydrogen leading to major reductions in transportation carbon emissions would be only about 50/50.

Hydrogen may well turn out to be THE answer for future transportation fuels. The harder we work at it, the more likely it will be. But the possibility that its currently serious cost and storage problems might not be entirely overcome and that conventional technologies might further narrow its potential environmental advantages cannot be dismissed. And if, despite our best efforts, hydrogen cannot be made competitive, what will we do then?

Is it OK to do nothing in the meantime?

Clearly, if hydrogen failed to become a competitive energy carrier by 2050, the answer to this question would be no. But for the sake of argument, let's assume success. If hydrogen technology ultimately succeeds, this is not a trivial question. Climate analysts have shown that there are many paths to stabilization of atmospheric GHG concentrations at levels that may not do an unacceptable level of damage to the climate (450 ppm? 550 ppm?). Some of these paths allow atmospheric concentrations to temporarily "overshoot" the target concentration levels, but such paths require much greater emissions reductions afterwards. However, if success in achieving the hydrogen economy makes such reductions much easier and cheaper to achieve in the future, overshooting could be a good choice.

On the other hand, the effect of GHGs on climate is essentially cumulative: a ton of carbon kept out of the atmosphere today is a ton that doesn't have to be kept out in the future. Energy infrastructure and energy using equipment are long-lived. Even if hydrogen is ultimately successful, it will take decades before it fully replaces conventional technology. Furthermore, the most economical sources of hydrogen today are the fossil fuels we must ultimately avoid or use only in combination with cost-adding sequestration. When hydrogen is first introduced, it is likely that the most economically competitive way to produce it will be from fossil fuels without the added cost of sequestration. Initial production from fossil fuels without sequestration would further delay the potential GHG benefits of the hydrogen transition. Suppose hydrogen technology is not ready for commercial success in transportation for 15-20 years, that it takes 15-20 years to replace the majority of the energy infrastructure, and that initially hydrogen is produced from natural gas, petroleum or coal without sequestration. Waiting 30-40 years for carbon-free hydrogen would be the right choice only if there are no cost-effective options to pursue in the meantime.

Will the transition just happen, or are policies needed?

Unless there is a compelling business case for hydrogen that depends entirely on private benefits (cheaper, faster, safer, better) rather than societal benefits (energy security, clean air, GHG mitigation), the answer is that strong policies will be needed. Existing analyses indicate that even if the program is successful, hydrogen will preferable to other advanced technologies as a light-duty vehicle fuel only when its societal benefits are taken into account. If this is the case, then strong policies will be needed to stimulate the transition to hydrogen and permanent policy interventions will be necessary to sustain a hydrogen-based transportation system.

But given what we have said above, it would not be wise to count on hydrogen and hydrogen alone as the only greenhouse gas strategy for transportation. A more robust policy portfolio is needed, one that leads toward a hydrogen economy while providing other options in case they are needed. This policy portfolio should be guided by five simple principles:

- Create technological options through R&D
- Create market signals encouraging GHG mitigation
- Make continuous progress in GHG mitigation
- Promote technologies that enable hydrogen transportation
- Educate and inform the public

The first and most obvious policy needed is support for research and development to create the technological basis for the transition to a hydrogen economy. Direct funding of hydrogen and fuel cell R&D by the government insures that needed research will be done, and also insures that the government stays well informed about the status of hydrogen technology and the challenges facing it. But hydrogen and fuel cell R&D is not enough. Because the technology for the transition to hydrogen may not be ready on schedule, we must also carry out the R&D necessary to hedge our bets. Hedging works best when the success of the alternatives is not related to the success of hydrogen technologies. Advanced internal combustion engines not just for highway vehicles but for aircraft and other transportation vehicles, and low-carbon renewable fuels would seem to be good choices.

Probably the most important way to stimulate the needed R&D is to convey a clear message to the transportation sector that GHGs must and will be reduced, and that low-GHG technologies and energy sources will therefore have extra value in the future. Conveying the importance to society of greenhouse gas mitigation through market signals is critically important. First consideration should be given to carbon cap-and-trade systems because of their theoretical advantages and widespread and growing acceptance as a global strategy. But carbon taxes or carbon emissions standards could also work effectively.

We should make continuous progress in mitigating GHG emissions from transportation. This means chiefly insuring continuous improvement in the energy efficiency of transportation. This can be done by efficiency standards of various forms, or by market based mechanisms such as “feebates”. By making steady progress we avoid wasting the opportunities that cost-effective mitigation options offer today, thereby reducing the burden on future generations, and we also buy time for the technological advances needed for an efficient and effective transition to hydrogen. Implementing meaningful policies today is also a key motivating force for technological change. Making it clear that GHG mitigation must and will be done creates a favorable business climate for investment in hydrogen and other mitigation and sequestration technologies.

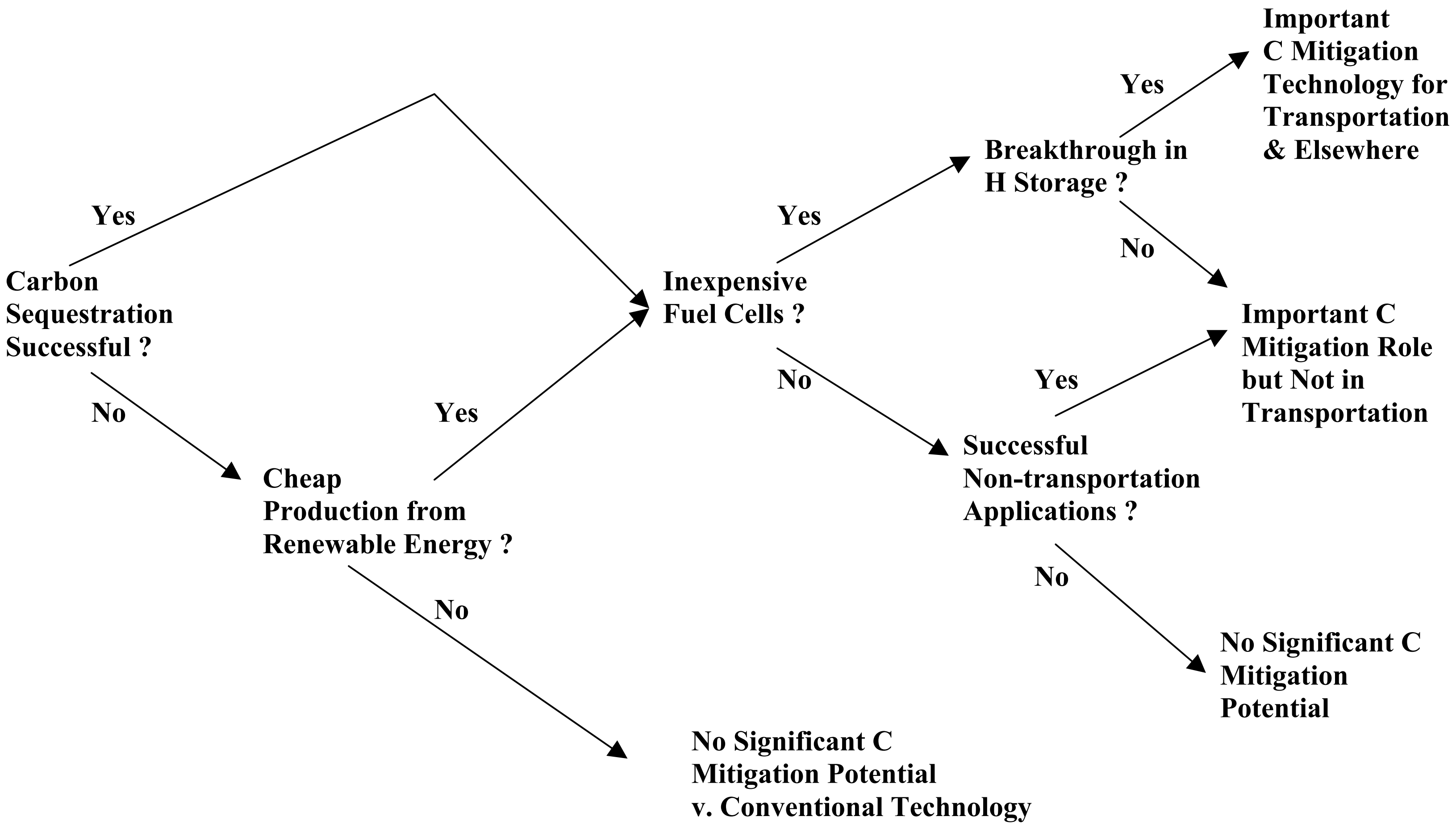
While it is important to include market signals in a comprehensive policy framework, it is just as important not to rely on pricing signals alone. Not all energy markets will respond efficiently to price signals. For example, most manufacturers believe that consumers consider only the first 2-4 years worth of fuel savings in their decisions about fuel economy, even though a new U.S. passenger car has a life expectancy of 15 years. Similar market imperfections exist in other sectors, as well. And there are other important complications. Airports, ports and highways are provided by governments not markets, and in other modes competition is often very limited. Governments also strongly influence the patterns of land development that in turn influence the need for transportation and the choice of modes, and so on. To believe that a single price switch can be thrown and that the problem of transportation's GHG emissions will be solved is naïve.

At the same time we are hedging our bets by advancing technologies unrelated to hydrogen, such as biofuels and efficient internal combustion engines, we should promote the market success of technologies that will help enable hydrogen fuel cell vehicles. Paramount among these is hybrid vehicles. Hybrid vehicles share many components with fuel cell vehicles, such as batteries, electric motors, controllers, inverters, sensors and sophisticated computer control systems. If hybrid vehicles are successful, they will not only directly mitigate GHG emissions by increasing fuel economy up to 50%, but they will enable learning-by-doing and provide economies of scale that will reduce the cost and improve the quality of essential components of hydrogen fuel cell vehicles. Early sales of hybrids can be effectively promoted by direct subsidies to purchasers and tax incentives, but hybrid technology will also benefit from higher fuel economy standards or feebates.

Educating and informing the public is essential. At present, the public does not accept the need for policies that will raise the price of carbon-based fuels. Both government and industry have a responsibility to inform the public about the need for such market signals. Even more importantly, the public should understand the larger context in which all these policies are working to create a transition to a cleaner, more secure and sustainable energy future.

Betting on hydrogen and hydrogen alone to solve the problem of climate change leaves society with an unbalanced policy portfolio. It ignores both the possibility of failure and the likelihood of partial rather than complete success. It overlooks the value of hedging and of buying time by making cost-effective, significant GHG reductions during the decades in which the technology for the hydrogen economy is being developed, the transition to hydrogen is being made, and renewable, nuclear and fossil sources with carbon sequestration are replacing greenhouse gas-emitting conversion processes. While we are working towards and waiting for H_2, there is a great deal more that can and should be done.

“Decision Analysis” of Hydrogen Energy as A Carbon Dioxide Mitigation Strategy for Transportation



Ford's Vision for a Hydrogen Transportation Future

Ford Motor Company

Summary

Ford Motor Company believes that hydrogen offers the promise of reducing mobile and stationary emissions, as well as the potential to improve our nation's energy independence. We are investing significant resources to advance and demonstrate hydrogen vehicle technologies, such as fuel cells and hydrogen internal combustion engines. Given the enormity of the challenge, no one can do it alone, and we believe that industry, energy providers, and government partnerships and long-term vision will be required to undertake this critical endeavor.

Benefits of Hydrogen

Hydrogen offers many attributes as a transportation fuel. It can be derived from various sources. This diversity means that different geographic regions can obtain hydrogen from whatever feedstock is available which would tend to reduce concerns over regional energy security. Hydrogen is a "clean burning" fuel, contributing to significantly reduced local emissions where it is used. If hydrogen is derived from renewable resources, if carbon is successfully sequestered, or if environmentally benign nuclear power sources can be developed, the total environmental impact of hydrogen as a fuel would be minimal.

- For the transportation sector, much of the discussion of hydrogen as a fuel has been centered on the fuel cell. While this is the most likely "end game" for sustainable transportation, in the shorter term hydrogen is attractive since it can be efficiently burned in conventional internal combustion engines. Hydrogen has a wide combustion range which means that hydrogen fueled engines can operate on a wider range of air-fuel mixtures than gasoline engines, and can run lean for more efficiency with minimal pre-ignition or knock. The maximum brake thermal efficiency[1] of a hydrogen ICE is approximately 38%, about 25% better than a gasoline engine.
- Converting existing engines to run on hydrogen requires modifications to the engine such as new fuel injectors designed to handle hydrogen gas, revised ignition system, new high compression pistons, modifications to the engine controls software and adding a supercharger. These engine changes would leverage the large manufacturing infrastructure already in place to produce gasoline- and diesel-fueled engines which can affordably be converted to run on hydrogen. In addition, key vehicle subsystems needed for fuel cell vehicles, such as on-board hydrogen storage, fuel handling, instrumentation and sensors, could be developed first on a hydrogen ICE vehicle.
- Taking the hydrogen ICE vehicle one step further along the evolutionary path by adding a hybrid electric powertrain provides further efficiency improvements. Here again, technologies such as durable and efficient batteries, electric motors, electronic inverters/converters and controls developed for H_2 ICE HEVs would also support development of fuel cell vehicles.
- Thus, a H_2 ICE could serve as a bridging action -- providing significantly lower tailpipe emissions and better fuel efficiency, while helping to provide an economically viable path towards hydrogen fuel cell vehicles. H_2 ICEs could also help develop vehicular demand for the installation and expansion of a hydrogen refueling infrastructure – the lower cost of a H_2 ICE means that for the same cost, more ICEs than fuel cell vehicles could be produced and put into the market.

Hydrogen Challenges

Many issues must be resolved before hydrogen can become a viable fuel alternative:

Vehicle:

In general, for any new hydrogen fueled vehicle to be viable for high volume sales, it will need to provide equal or better function than a conventional vehicle at comparable cost very soon after public introduction. (Or public policy incentives would have to exist that temporarily cover the gap between the cost of the vehicle and what the customer is willing to pay for it. This is discussed in somewhat more detail in the policy section below.) Although there will be a few "early implementers" who are willing to pay a premium price for new technologies, the automobile is becoming a commodity to customers who are uncompromising in their demand for performance, function, quality and affordability. The hydrogen vehicle is faced with many challenges, many of which will require technical breakthroughs rather than simply further development of existing technology:

- Low cost, high density, on board hydrogen storage systems that do not add significant weight to the vehicle or reduce its cargo or passenger carrying capacity. H_2 storage provides the largest vehicular challenge to the viability of a hydrogen fueled vehicle. A minimum of a 300 mile range is required which results in storage goals of
    - 2010: 2.0 kWh/kg (6 weight percent), 1.5 kWh/liter, $4/kWh
    - 2015+: 3.0 kWh/kg (9 weight percent), 2.7 kWh/liter, $2/kWh

  Technologies being investigated include compressed gaseous hydrogen tanks, chemical hydrides, metallic hydrides, and carbon nanotubes, but none can meet these aggressive targets yet. Because H_2 ICEs are less efficient than fuel cells, their range will be somewhat less. This, however, was considered when the FreedomCAR Hydrogen Storage goals were set with the expectation that a storage system meeting the 2015 goals, in particular, will provide acceptable range to either customer.
- Lower cost fuel cell systems with total costs an order of magnitude or more lower than the cost of today's developmental fuel cell systems. 2010/2015 targets of $45/$35/kW are necessary to be cost competitive with conventional gasoline or diesel ICE technologies. (Costs much higher than this are unlikely to encourage customers to make the switch from known technology.) Improvements needed to contribute to the achievement of this goal include:
    - Lower cost fuel cell components such as cathodes and anodes which require less (or no) precious metal.
    - Fuel cell stack design improvements addressing present reliability, durability, and manufacturability issues.
    - Improved, lower cost, smaller size and more durable and reliable power electronics and batteries.
- Fuel cell enabling technologies such as:
    - Fuel cell systems that are tolerant of broad ranges of operating temperatures and variations in hydrogen purity
    - Compressor/expanders which are smaller, more efficient and quieter
    - Drive motors which are more efficient and lower cost
    - Sensors which are smaller, lower cost and more effective

- A "given" for any new vehicle technology is that it meets the same safety, quality/durability (10 years/150,000 miles) and functional requirements as other vehicles on the road.

Infrastructure:

Establishing the required hydrogen retail infrastructure will be an immense and expensive proposition. From an auto manufacturer's perspective, the existence of an expansive refueling infrastructure is critical to management commitment to high volume vehicle production. Some have estimated that hydrogen fuel will need to be available at 25-50% of urban and 50-70% of rural filling stations before consumers will feel confident enough to purchase a hydrogen vehicle. The estimated costs of creating this infrastructure exceed tens of billions of U.S. dollars.

- Means for hydrogen transportation and delivery need to progress to the same extent as the gasoline distribution system today. Today's usual transport of compressed gaseous or liquid hydrogen by tube tanker trucks will have to be replaced by significantly higher capacity transportation systems that may require a mix of local, regional and central hydrogen production facilities feeding the transportation and delivery system.
- Today in the United States, local, regional and state governmental agencies are responsible for setting codes and standards. Thus, it is not unusual to find different requirements for the operation, storage and maintenance of hydrogen-fueled vehicles in different locales. This makes the production of vehicles that can be widely sold and operated very difficult. Significant changes in Codes and Standards (C&S) are required to:
    - Develop and provide uniform C&S throughout the United States and developed world to permit the deployment and operation of hydrogen-fueled vehicles and a hydrogen infrastructure.
    - Develop a common C&S permitting template that can be used by local, regional and state permitting authorities.
    - Modernize existing C&S based on future research data on hydrogen characteristics and safety.
    - Develop industry standard C&S that can be universally applied to vehicles regardless of where they will be sold.
- Similarly international harmonization or homologation of hydrogen codes and standards is needed. The DOE and U.S. code and standard setting bodies can assist with this.

Timing

Although it is very difficult to predict the advent of technology, the U.S. DOE has suggested a broad timeline to determine the practicability of fuel cell commercialization. In its fuel cell report to Congress,[2] DOE suggested (and Ford concurs with):

- **2004-2009**: controlled fleet test and evaluations to evaluate use of fuel cell vehicles in real world conditions
- **2009-2015**: commercial readiness demonstrations to demonstrate viability of fuel cell vehicles in higher volume fleet usage, and the expansion of hydrogen refueling stations to provide convenience
- **2015 and beyond**: determine whether there has been sufficient technical progress with the fuel cell and vehicle technology to permit auto manufacturers to make decisions regarding

commercialization, and sufficient demand for energy providers to make H_2 available at substantial numbers of fueling stations.

If the 2015 decision point results in a commitment to go forward with hydrogen vehicles and widespread availability of hydrogen refueling stations, Ford can envision a scenario where auto companies would begin to shift production from gasoline ICEs to hydrogen at the same time energy providers begin to add significant numbers of hydrogen pumps. It is likely that the new vehicles and expanded infrastructure would arrive in the market together a few years later. Because of their lower costs and similar environmental benefits relative to fuel cells, H_2 ICEs may initially dominate the hydrogen powered vehicle market. But, over the next ten to fifteen years there may be a shift toward increasing numbers of fuel cell vehicles as they become more refined, more publicly accepted and as costs are reduced. Successful fleet testing of H_2 ICEs during the 2005-2015 timeframe could play a key role as a bridging strategy to this vision.

Policies Needed

- Ford strongly supports cooperative partnerships among the auto industry, fuel providers, and government, like the California Fuel Cell Partnership (CaFCP), FreedomCAR Program and Hydrogen Fuel Initiative to help speed hydrogen research to lower the cost of fuel cells and hydrogen fuel, storing hydrogen on vehicles, and developing infrastructure.
- Continued R&D programs to address the technological issues with fuel cells and hydrogen storage and infrastructure
    - Develop and promulgate uniform Codes and Standards
    - World-wide homologation of Codes and Standards
    - Identify sustainable hydrogen production alternatives
    - Carbon sequestration research
    - The CaFCP has brought key stakeholders to promote discussion of critical issues and identify key activities that are necessary to advance the commercialization of fuel cell vehicles. Through the demonstration of fuel cell vehicles and fueling technology, the partnership has developed a substantial experience base that is constantly growing. By communicating lessons learned to other organizations that wish to accomplish similar objectives, the CaFCP is making a contribution to fuel cell vehicle commercialization.
- Once the technologies (both vehicle and hydrogen fuel and delivery) have advanced beyond the research stage, the industries involved will need some form of incentive to increase volume to achieve the economies of scale that will help start driving the costs down. Policy actions such as the following can help to do this:
    - Encouraging or mandating government fleet purchase of hydrogen fueled (H_2 ICE and FCEV) vehicles and hydrogen fuel.
    - Providing financial incentives to purchasers of hydrogen fueled vehicles and to the use of hydrogen fuel.
    - Ford and many others like the broad based CLEAR Act Coalition and U.S. Energy Futures Coalition believe that temporary incentives in the form of customer tax credits will be required to accelerate the purchase and acceptance of these advanced vehicles in the marketplace, as well as to encourage the development of the required hydrogen retail fueling infrastructure. Generally speaking customer incentives should

be performance-based, scaled relative to the incremental costs of the advanced technology, and in place long enough to generate sustainable volumes and manufacturing economies of scale.

- The financial community, government and industry need to find a way to sustain the interest of investors in emerging technologies that support the vision of a hydrogen transportation future, but cannot promise a quick pay back of investment funds. It will likely be years before many of the emerging, high-tech companies needed to launch the hydrogen economy achieve ongoing profitability; yet, preservation of those companies over the long term is critical to the success of a hydrogen economy.
- Education and outreach are needed to train government officials, permitting agencies and officials, emergency personnel and the general public about the safety and potential benefits of hydrogen.

Definitions:

- *Lean Operation: Engine management that delivers more air (and less fuel) than necessary to burn the air/fuel mixture for improved engine efficiency.*
- *Pre-Ignition: The tendency of fuel to ignite spontaneously due to local high temperatures (hot spots) in an engine's cylinder.*
- *Knock: The sound made by the engine when the fuel ignites prematurely due to poor engine timing or use of low octane fuel. The ability to maximize power and fuel economy by optimizing spark timing for a given air/fuel ratio is limited by engine knock. Detecting knock and controlling ignition timing to allow an engine to run at the knock threshold provides the best power and fuel economy. Damage to pistons, rings, and exhaust valves can result if sustained heavy knock occurs. Additionally, most automotive customers find the sound of heavy engine knock objectionable.*

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[1] Brake Thermal Efficiency: The ratio of work done by an internal combustion engine to the amount of energy contained in fuel as measured on a dynamometer (sometimes called a "brake").

[2] U.S. Department of Energy. 2003. *Fuel Cell Report to Congress*. February 2003. Available at: http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/fc_report_congress_feb2003.pdf.

The Transition to Hydrogen as a Fuel

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Most of today's hydrogen is made from natural gas in large centralized plants because the predominant customers, refineries and chemical plants, need large amounts of hydrogen at these industrial locations. The hydrogen is either made where it is used or is put into large pipelines which can supply a number of plants. This is currently the least costly way to meet this demand.

If hydrogen is to be used as a transportation fuel, different production methods and delivery methods need to be considered to deliver it to a broad geographic area. No longer will very large amounts be needed at one location, but small amounts will be needed over a broad region. So the system will be much different than what we have today, but one thing will remain the same: the least costly methods will still fill the demand.

There is no single best production method for every region

There are several methods available today that can be considered for future hydrogen production and that may meet the three critical criteria for any future energy system — low cost, low GHG emissions and abundant domestic availability. Natural gas reforming, coal gasification, grid-based electrolysis, renewable-based electrolysis, biomass conversion and nuclear electrolysis are examples.

Each of the above technologies satisfies the three criteria in different ways and to different extents. Natural gas reforming has historically been inexpensive, emits some GHGs and comes mostly from domestic sources, but imports are rising which could affect future prices. Coal gasification is inexpensive for very large-scale production, yields twice the amount of GHGs to produce a given amount of hydrogen, and is made totally from domestic resources for the foreseeable future. Conventional grid electrolysis is very expensive, can produce as much GHGs on a life-cycle basis as coal gasification (depending on the source of electricity) to produce a given amount of hydrogen, and is all from domestic resources. Renewable electrolysis (photovoltaic and wind) is even more expensive, produces almost no GHGs, is from domestic resources, but is limited in supply in highly populated regions. Biomass conversion is expensive, produces almost no GHGs and comes totally from domestic resources, but a limited absolute amount is available in the United States. Hydrogen from nuclear electrolysis is more expensive than from coal or natural gas, produces almost no GHGs and is domestically available, but has disposal and security issues.

None of these technologies and feedstocks totally satisfies all of the criteria. The low-cost methods rely on imports or have high GHG emissions. The low-import and low-GHG options have high costs or limited availability. Some options clearly will work better in different parts of the United States, just as today different electricity generation methods work better than others in different regions. There is no one best production method that will work best everywhere. This flexibility, in terms of production method, is one of the strong advantages of using hydrogen as a fuel.

The future proportion of the hydrogen made from each of the methods depends on many factors, including the cost of hydrocarbons, the demand for hydrogen, how technological advances help to lower the costs of each technology, how society values low-GHG fuels, whether or not CO_2 can be safely and economically sequestered and what methods fit best with the regional supply and demand needs at any time. As these will change through time, so too will the choices for the future hydrogen generation and distribution infrastructure. We could see a mosaic of all of these different feedstocks used in different sizes in different situations. This will start to grow from the existing hydrogen, hydrocarbon and electricity infrastructure.

Demonstrations and pre-commercial phases

In this earliest phase, where we are today, hydrogen demand is very low with dispersed small fuel cell car demonstrations in a growing number of states transitioning into small pre-commercial fleet activity. Hydrogen availability is the primary fuel criterion. Initial hydrogen fuel demand will primarily be satisfied from existing hydrogen producers delivering hydrogen in small quantities by truck to relatively few, very small refueling stations. There are several industrial gas suppliers that can deliver from a number of terminals now with fairly broad geographic coverage. This is the most logical supply route to use because it minimizes investment until it is clear that hydrogen-fueled cars and trucks will be successful. This supply route however, has limited viability as it is very high-cost. Costs are as much as 5 to 10 times today's gasoline cost. As more hydrogen is needed to fuel an ever expanding demand over a broad geographic area, a different, lower-cost method will be needed to fuel a commercial growth period. Government support is needed for both demonstrations and for the research to develop the lower cost methods. The most promising ones appear to be small natural gas reformers and small electrolyzers.

Growing towards broad geographic availability

Once the technology moves out of the pre-commercial phase, costs become much more of an issue. Small distributed hydrogen production located at refueling stations will be the best method to meet customer demand in the medium term, starting 5 to 10 years from now. These refueling stations are likely to be located at a small fraction of today's gasoline stations and dispense both hydrogen and conventional fuels. The oil and gas industry has shown a real interest in helping to develop these technologies and in understanding how today's gasoline stations can evolve into hydrogen stations. The hydrogen will be produced at the station using either small natural gas reformers or small electrolyzers using off-peak grid power. Since either natural gas or electricity is available everywhere, this distributed production method should be practical for some time. These methods are attractive because (1) the hydrogen cost is much lower than from hydrogen delivered by truck, (2) the investment per station is not exceedingly large and (3) only a small fraction of today's stations (10 to 25%) need to be converted to begin the transition.

As it is not practical to capture and sequester GHGs from small distributed natural gas reformers and as most electricity is now made from fossil fuels, this will not start out as a low-GHG production route. Renewably produced electricity could be used where and when it is economically available in addition to off-peak electricity, resulting in lower GHG emissions. Together, renewably based electrolysis and natural gas reforming could form a near-term pathway to a lower-GHG future at reasonable cost.

Getting this process started involves overcoming the traditional chicken and egg problem. As there is no incentive for the current fuel suppliers to invest in a large number of stations that will sell very little hydrogen, some form of government action will be needed to provide incentives until volumes grow to the point of profitability. Although the hydrogen costs using these distributed methods should be much lower than from truck delivery, the fuel cost for a vehicle will likely still be higher than today's gasoline fuel costs.

Eventually small grids of these stations interconnected by pipelines may develop with some producing hydrogen and others just dispensing hydrogen. To further lower costs, these stations will eventually start to make both hydrogen and electricity (from a fuel cell) at the station. The electricity would power either an attached convenience store or perhaps a supermarket. These kinds of stations are ideal for refueling between 200 and 2000 cars per day.

Long-term, low-cost, large-scale production

Eventually, when a substantial hydrogen fuel market is established, the cost can be further lowered by making hydrogen in large centralized plants located near population centers - just as power plants generate electricity today. This hydrogen can then be shipped by pipeline to refueling stations that will store and dispense to the public. These large plants may use natural gas, coal, biomass or nuclear methods to make inexpensive hydrogen. In these plants, any CO_2 produced can be captured for possible sequestration. These plants work well when there are large concentrations of hydrogen cars in a region so that per-vehicle distribution costs are low; at least 150,000 cars in a local region seems to be the point at which this may occur. It is not possible to predict when these high densities will arrive, but it is very unlikely to happen for at least 25 years.

Some parts of the country will not have population densities large enough to support centralized production and in these parts distributed production methods will continue to be the most practical solutions. In either case the refueling stations already converted to handle hydrogen will continue to be the refueling locations. This will help to keep stranded costs of putting in the distributed infrastructure and then transitioning to a centralized system low.

It is likely that the lowest-cost hydrogen will be made at large centralized plants that co-produce both electricity and hydrogen and that direct the hydrogen to nearby population centers. For example, a future coal gasification plant running 80% coal and 20% biomass making both electricity and hydrogen with the CO_2 captured and sequestered could meet all of the energy system criteria. It can produce hydrogen competitive with today's petroleum costs, it will not release CO_2 to the atmosphere and it will be made entirely from domestic resources. This technology, however, is not perfected yet and needs more research before it is ready for use. This is also the case for some other large-scale technologies like nuclear methods.

The answers are not clear, especially in the long term

What the future hydrogen fuel system mosaic will eventually look like is not crystal clear. With all of the options available to make hydrogen, there is no one solution that best fits all cases. Different solutions are most practical in different regions and at different times through the transition.

Technology development, especially in carbon sequestration viability and in renewable electricity cost reduction can radically shift the future mosaic from what we might expect today.

Transition along this path is not risk-free and several areas need to be emphasized for the public and private sector to jointly pursue. Most important is technology research and development to answer the critical questions about the viability of fuel cell car technology and the ability to make inexpensive hydrogen as broadly and safely available as today's fuels. Neither question has yet to be answered to the extent that long-term decisions can be made. In addition to research is the need for more demonstrations of new technologies to gauge the current state of development and to gauge the public's willingness to change from our current infrastructure. Of the production technologies, small natural gas reformers and electrolyzer development should be emphasized as the most important solutions to the initial infrastructure.

It is apparent that hydrogen costs are going to be more expensive, at least initially, than our current fuels. Because of this, a transition to hydrogen as a fuel is unlikely to happen for purely business reasons. The initial markets will be too small and the risks of long term markets developing too high. Some form of market-based incentive is going to be needed to encourage hydrogen fuel use. And, if society places a higher value on making hydrogen in low GHG-emitting methods, which appear to be more expensive, then further market incentives will be needed to encourage using these methods.

Hydrogen Production and Supply Infrastructure for Transportation - Discussion Paper

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Hydrogen is a widely used industrial gas for a variety of applications such as the refining of crude oil, production of ammonia and methanol, the production of semiconductor chips, processing of edible oils, surface treatment of machined metal parts, etc. The annual worldwide production of hydrogen is about 50 million (metric) tonnes, the large majority (95%) of which is made and captively used within large refineries, and ammonia and methanol plants. There is also a smaller but rapidly growing merchant hydrogen industry, which makes and supplies about 2.5 million tonnes per year of the gas to third party customers. This market is well developed and rapidly growing, particularly in the United States, Canada, and Western Europe. To put this in some context for the present discussion about hydrogen as a transportation fuel, the 2.5 million tonnes/year is enough hydrogen to fuel a total of about 14 million hydrogen cars if they filled up once every 8 days with 4 kg of hydrogen each time.

Today hydrogen is most economically produced from natural gas (mostly methane) using a process called steam reforming. In this process, the hydrogen bound in the methane as well as hydrogen from steam is released. In addition hydrogen is also obtained as a by-product from petrochemical and chlorine-alkali plants. Another commonly used process is the electrolysis of water but this process is significantly higher in cost and is usually only used for very small-scale production and in remote locations where hydrogen delivery is not feasible.

The production and delivery of hydrogen for industrial uses is very mature technology. The hydrogen is often produced in large plants to take advantage of the economies of scale. The hydrogen from these plants is distributed as a gas via dedicated pipelines, via over-the-road high-pressure gas tube trailers, or as a super cold liquid via special cryogenic tankers by road and even by rail. These deliveries that number in the tens of thousands of trips and cover millions of road miles per year have been accomplished with an impeccable safety record over the last 4-5 decades. Today there are more than 1,000 miles of hydrogen pipelines serving large refineries and chemicals plants in several locations around the world. A massive build-up of hydrogen pipelines in the future to serve a hydrogen economy should have the same safety characteristics as the widespread natural pipeline networks that exists today. Hydrogen is no more dangerous than the gasoline that we are so accustomed to today. In many ways hydrogen has several mitigating factors that may make it more safe in an accident. For example as a rapidly diffusing gas any escaping hydrogen from a ruptured gas tank will vent straight up and leave the area of the accident very rapidly, while gasoline will pool on the ground and continue to burn with a very luminous flame. Thus passengers in a hydrogen car would likely suffer fewer burn-related injuries than in a gasoline car.

In the early days of hydrogen vehicle development (over the next 5-10 years) adaptation of the existing distribution infrastructure to the needs of the fuel application will be the most likely path forward. Today there exist many tens of hydrogen fuel stations in the United States, Europe, and Japan serving very small numbers of hydrogen demonstration vehicles. A large number of these stations are based on some form of delivered hydrogen to the site with the station having the ability to store, compress, and dispense hydrogen at high pressure to the tanks onboard the vehicles. Hydrogen hauled in via high-pressure tube trailers[1] can work for up to 25 cars/day at a site. For larger fleets up to about 500 cars per day an installed fuel station with liquid hydrogen deliveries and storage on-site would work very well.

In addition to building fixed fuel stations for dedicated fleet projects which refuel at the same site, novel approaches like mobile fuelers which can be relocated at will and which can fuel vehicles at different sites as the need changes are also being introduced to serve the early demonstration needs. These mobile fuelers can be either refilled at a central plant and brought to the use point without the requirement for any utilities (external power or cooling water, etc.) or may have their own hydrogen generator such as a water electrolyzer to produce the hydrogen from water and electricity. Such units have begun to be introduced particularly in California where much of the fuel cell car activity is focused.

In locales where centrally produced hydrogen cannot be readily accessed the production of small quantities of hydrogen via reformation of other fuels such as natural gas, propane, butane etc. or via the electrolysis of water at the site of the fuel station will need to be adopted. Examples of this approach can be seen in Las Vegas, Tokyo, Iceland, and elsewhere. These small plants are still under development and are not commercially viable today but in some regions of the world there may be no other option to enable hydrogen fueling. As these units move down the development track and become reliable and achieve cost viability and as the demand for hydrogen fueling grows, it is foreseeable that such factory built reformer units could achieve low costs due to volume production. These new small-scale on-site reformers could handle fleet growth to fuel about 250-300 cars/day. These options therefore may have a life span that stretches from now until well into the future depending on their achieving the aforementioned objectives.

Water electrolysis is a very convenient way of starting to supply very limited numbers of vehicles. Systems small enough to serve even a single car may be deployed. The early stages of retail market development will be significantly enhanced by the option of home refueling using electrolysis, possibly with off-peak power rates. Generally the operating cost of electrolysis is high unless cheap electric power is available in off-peak hours.

In a future large and growing hydrogen economy (20+ years) it is likely that hydrogen will again usually be centrally produced at large facilities to achieve maximum economy of scale, reasonably near where it is needed (e.g. a large metropolitan area), and distributed to a large number of fuel stations via dedicated pipelines or as liquid hydrogen. The stations will have the ability to store and dispense the fuel much as they do today with petroleum fuels. It will still likely be produced from the same feedstocks as today — i.e., natural gas for some time to come. However, as renewable energy technologies reach a level of technology and cost maturity to compete with fossil sources, there will begin to be a shift away from current fossil-based hydrogen production to these alternatives.

A 1998 DOE study estimated the untaxed cost of hydrogen produced at various scales at the fuel station or delivered from large regional or remote reformers and dispensed at 5,000 psi to the vehicle. As expected there is a strong scale dependency of the hydrogen cost. The untaxed price of hydrogen to the vehicle ranges from almost \$7/kg (or GGE = gal gasoline equivalent) for a home-electrolytic unit capable of filling one car per day to about \$2.50/kg (or GGE) for very large-scale hydrogen plants capable of filling some 50,000 cars/day. However, it is important to recognize that significant capital investments are required to install the large-scale facilities to achieve the lower costs, which will only occur when there is clear indication of market demand. The untaxed hydrogen cost is higher than the average U.S. retail gasoline price, which is fully taxed (<\$2/gal) even at the very largest scales of production. Hydrogen would need to receive favorable tax incentives to permit market entry. The greater efficiency of fuel cell vehicles versus IC engine vehicles should also help to close the price gap between hydrogen and gasoline to help in market entry.

In addition to the potential need for favorable tax treatment as indicated above, policy efforts should also be focused on fostering harmonization of codes and standards for hydrogen fueling equipment and stations. This would be a great help in streamlining the permitting process for the build-out of the infrastructure. Currently no uniform codes and standards exist for the fuel applications of hydrogen and consequently local authorities largely decide requirements on a case-by-case basis, which often creates a barrier to timely construction of fuel stations. The federal government should play a coordinating role among the various code-making bodies in the United States, and lead the negotiation for harmonization with international bodies. Examples of codes and standards needed include on-board storage pressure (currently varies between 3,600 psi and 5,000 psi and development is underway to move up to 10,000 psi), and the type of nozzles used for filling the vehicle tank, as no uniform standard exists. Air Products' experience is that it takes a lot of time to convince local authorities of the safety of the hydrogen stations since we have no uniform standards to reference. Another area that requires significant attention is the education of the public about the use of hydrogen and its safety considerations to avoid the kind of undue fear and public opposition to fuel station installations that has been seen recently in London.

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[1] A tube trailer is a set of high-pressure tubes mounted on wheels that transports hydrogen gas at a pressure of 2600 psi (a limit set by the DOT) over the road in regular commerce. They range in capacity from 60,000 SCF to 160,000 SCF.

policy

Carbon Sequestration/ Coal Gasification

technology

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Carbon Dioxide Sequestration/Coal Gasification

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Carbon Dioxide Capture and Storage in Underground Geologic Formations

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Introduction

Over the past several hundred years, atmospheric CO_2 concentrations have steadily increased and have now risen to over 370 ppm from the pre-industrial level of 280 ppm. Increases in CO_2 concentrations are attributed mainly to burning coal, oil and natural gas for electrical generation, transportation, industrial and domestic uses. Today, globally, over 20 billion tons of CO_2 are emitted into the atmosphere and of that, 5.5 billion tons are from the U.S. alone. There is growing consensus that increases in CO_2 concentrations will disrupt the earth's climate, cause sea level to rise enough to flood many low-lying coastal regions, and damage sensitive ecosystems. Experts believe that to avoid significant disruption of the climate system and ecosystems, CO_2 concentrations must be stabilized within the next several decades. At today's emission rates, atmospheric CO_2 concentrations will continue to grow rapidly and, within 50 years, may exceed the levels needed to protect sensitive ecosystems and avoid flooding in low-lying coastal areas. This situation is even more dire when we consider that over the next fifty years CO_2 emissions are expected to double as the developing world's economies grow and the standard of living increases. To address this challenge, we need a multi-pronged approach to decreasing CO_2 emissions – more efficient production and use of energy, solar power, wind energy, biomass, switching to fuel sources with lower or negligible CO_2 emissions, and Carbon Capture and Storage (CCS), the subject of this paper.

CCS in underground geologic formations is unique among the options for reducing CO_2 emissions because it offers the promise for continuing to use proven reserves of fossil fuels in a CO_2 constrained future. The basic idea behind CCS is that CO_2 is captured before it is emitted into the atmosphere and then injected deep underground where it would remain for thousands of years or longer. The idea of CCS was first developed in the late 1970's but did not get much attention until the late 1980's when scientists and engineers began to look earnestly for ways to reduce CO_2 emissions to the atmosphere. In that short time it has emerged as one of the most promising options for deep reductions in CO_2 emissions. So much so that, in fact, today 1 million tons of CO_2 is being stored annually at the Sleipner Project beneath the North Sea. Several more commercial projects are in the advanced stage of planning: the In Salah project in Algeria, the Gorgon Project in Australia, and the Snohvit Project in the continental shelf offshore of Norway. In addition to these, more are under development.

The benefits of CCS are most applicable to large stationary CO_2 emissions such as those from coal and gas-fired electrical generation plants. Electrical generation plants account for about 35% of U.S. emissions today. The United States has abundant supplies of inexpensive coal which could provide a secure supply of electricity for hundreds of years. However, per Megawatt-hour (MWh) of electrical generation, conventional coal-fired power plants emit nearly twice the CO_2 of a modern natural gas combined cycle power plant. By eliminating CO_2 emissions with CCS, these abundant coal resources could assure a stable supply of energy for many generations to come. Emissions from large industrial sources of CO_2 such as refineries, cement factories, chemical processing, and smelting plants are also suitable for CCS. Importantly, in the future, it may also be possible to use CCS to reduce CO_2 emissions from the transportation sector (which account for nearly 35% of emission in the United States) if gasification of fossil fuels is used to produce hydrogen as a transportation fuel. The U.S. Department of Energy has announced plans to build a demonstration plant that would produce both electricity and hydrogen fuel from coal, while using CCS to eliminate CO_2 emissions to the atmosphere. If this is successful, CCS may accelerate the development of the infrastructure and technology for a CO_2-free hydrogen-based transportation system.

CO_2 Capture and Storage Technology

CCS is a four-step process where: first, a pure or nearly pure stream of CO_2 is captured from flue gas or other process stream; next it is compressed to about 100 atmospheres; it is then transported to the injection site; and finally, it is injected deep underground into a geological formation such as an oil and gas reservoir where it can be safely stored for thousands of years or longer (see Figure 1).

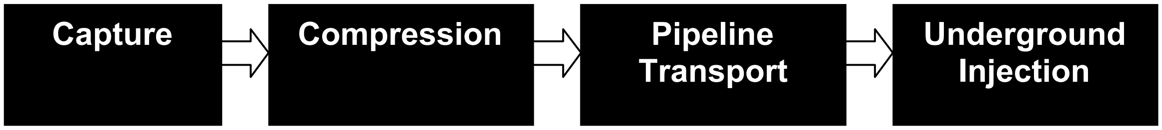

Figure 1. Schematic showing the major steps in the Carbon Capture and Storage Process.

Capture, Compression and Transportation Technology

Carbon dioxide is emitted from electrical generation plants and other combustion sources as a flue gas that contains mostly nitrogen and only from 5 to 15% carbon dioxide. Before it can be injected underground, the CO_2 must be separated from the remainder of the gas. Because of the low concentration of CO_2 in the gas, separating it is expensive, requires large surface facilities, and a lot of energy. For CO_2 capture from power generation or industrial boilers, capture technologies are grouped according to whether the CO_2 is captured after the fossil fuel is combusted, so-called post combustion capture ("end-of-pipe"), or prior to combustion (pre-combustion) in which chemical processes are used to gasify the fossil fuel to extract H_2 before it is combusted. Alternatively, from power stations, capture can be accomplished by using oxygen instead of air to combust the fossil fuels, thereby producing emissions of only CO_2 and water, from which the CO_2 is easily separated. Each of these capture technologies has benefits and drawbacks, which are summarized in Table 1 (for more details and cost data see Simbeck (2004), this volume). Of these separation technologies, only post-combustion capture is considered to be a well developed technology. In short, post-combustion capture using amine solutions is a demonstrated technology that could be applied broadly today, but costs and energy demands are high. The alternatives to post-combustion capture have significant advantages but more research, development and demonstration projects are needed before they are likely to be adopted by the power generation industry (Simbeck, 2004). Consequently, there is an urgent need for public and private investment in these new technologies.

Compression and transport of CO_2 are well established technologies that are used routinely today for enhanced oil recovery, beverage carbonation, and fire suppression. Regulations have been developed for the safe handling and transportation of CO_2 in industrial settings.

Table 1. Comparative benefits of post-combustion, pre-combustion and oxygen-combustion.

Technology	Advantages	Drawbacks
Post-Combustion	• Mature technology for other applications (e.g. separation of CO_2 from natural gas) • Standard retrofit of existing power generation capability • Technology improvements and cost reductions possible with additional development	• High energy penalty (~30%) • High cost
Pre-Combustion	• Lower costs than post-combustion capture • Lower energy penalties than post-combustion capture • High pressure of CO_2 reduces compression costs • Combine with H_2 production for transportation sector • Technology improvements and cost reductions possible with additional development	• Complex chemical process required for gasification • Repowering of existing capacity needed • Large capital investment needed for repowering
Oxygen-Combustion	• Avoid the need for complex post-combustion separation • Potentially higher generation efficiencies • Technology improvements and cost reductions possible with additional development	• New high temperature materials are needed for optimal performance • On-site oxygen separation unit needed • Repowering of existing capacity needed

Injection and Storage Technology in Underground Formations

Carbon dioxide can be injected underground and stored in sedimentary basins (see Figure 2). Sedimentary basins are created by the gradual deposition and compaction of sediments that have eroded from mountains. Deposits, as thick as tens of thousands of feet, have accumulated in sedimentary basins around the world. Typically, sedimentary basins consist of alternating layers of coarse (sandstone) and fine-textured sediments (clay, shale or evaporites[1]). The sandstone layers, which provide the storage reservoir, have high permeability, allowing the CO_2 to be injected. The shale or evaporites layers have very low permeability and act as seals to prevent CO_2 from rapidly returning to the surface. Interestingly, naturally occurring CO_2 reservoirs exist in North America, Australia, China and Europe, proving that CO_2 can be stored underground for hundreds of thousands, even millions of years. In addition, many oil and gas reservoirs also contain large quantities of CO_2 confirming that oil and gas reservoirs can also store CO_2 over geologic time scales. The technology to inject CO_2 underground is mature and practiced routinely in CO_2 enhanced oil recovery projects. Little to no new injection technology will be required to enable CCS.

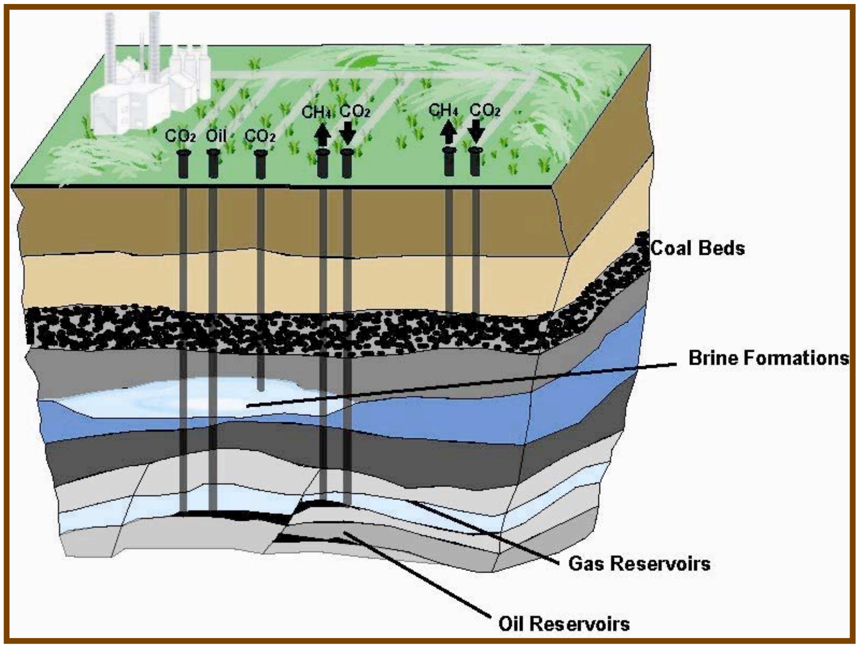

Figure 2. Schematic of a sedimentary basin with CCS. Enhanced oil and gas recovery from oil and gas reservoirs and deep unminable coal seams are also illustrated.

To ensure storage and capture integrity, locations for underground geologic storage of CO_2 would need to be selected to ensure that CO_2 would remain safely underground for thousands of years or longer. Regions with seismic or volcanic activity that could compromise the security of the storage site should not be selected. The best storage reservoirs are at depths of greater than 3000 feet below the ground surface, have several hundred feet of porous and permeable sands, and are overlain by at least one, and preferably more, thick and continuous seals. Under these conditions, CO_2 would be stored very securely and efficiently, with the density and physical properties of a liquid. Government regulations will need to be established and enforced to ensure that satisfactory sites such as these are selected for CO_2 storage.

Burruss (2004, this volume) describes how depleted oil and gas reservoirs are especially promising early opportunities for long-term storage because they have seals with 3-dimensional closure that have stood the test of time and a comparatively small effort will be needed to evaluate their storage potential. They are also attractive because CO_2 storage can be combined with CO_2 enhanced oil and gas recovery—a mature practice that is applicable to an estimated 80% of oil reservoirs. During the early stages of a storage project, the remaining oil can be extracted from the reservoir. Eventually, oil production will stop and the reservoir can be filled to capacity for long-term storage of carbon dioxide. The availability of an abundant low-cost supply of CO_2 could be a boon to the domestic oil industry. A similar idea can be applied to enhance the recovery of natural gas from deep coal beds. Tests of this concept are underway in the San Juan Basin in New Mexico. Similarly, it may be possible to increase production from natural gas reservoirs (Oldenburg et al., 2001).

Sandstone formations filled with salt water, such as the Mount Simon Formation in the Midwest, the Frio Formation along the Texas Gulf Coast, and the Central Valley in California, are estimated to have much greater storage capacity than oil and gas reservoirs. However, as pointed out by Burruss (2004), a significant effort will be required to characterize the storage reservoirs in salt-water filled formations and more importantly, to characterize the low permeability rocks that form the seal. The technology to characterize salt-water filled formations and their seals has already been developed for an analogous purpose, storage of natural gas to accommodate fluctuations in daily and seasonal demand. In the United States, natural gas is stored deep underground at over 400 sites, including over 50 aquifer storage sites, which are essentially identical to the salt-water filled formations that are contemplated for CO_2 storage. Natural gas storage technology is very similar to CO_2 storage and its successful application lends credence to the idea that CO_2 can be safely and effectively stored in salt-water filled formations.

The above discussion only focused on the potential for physically trapping carbon dioxide in deep geologic formations. Long-term storage is even more secure when the CO_2 dissolves in water or is converted to minerals such as calcium carbonate. From 10 to 30% of the injected CO_2 will usually dissolve into the formation water shortly after it is injected. For some storage sites, calculations have predicted that all of the CO_2 would dissolve within several thousand years. Once the CO_2 dissolves in the liquid, some fraction of that will be converted to minerals that will remain trapped over geologic time scales of millions of years.

Sophisticated 3-dimensional computer models are used to predict the performance of underground storage projects. While reservoir simulation is a mature technology, the capability of today's models needs to be extended to include accurate representation of the geochemical and geomechanical processes that are important for long-term storage. These models need to be validated by a number of site-specific studies that cover the range of geologic settings that could be used for CCS. International cooperation in computer simulation development and code intercomparison is helping to spur rapid improvements[2].

Current and Planned Capture and Storage Projects

Today there are four active geologic storage projects and at least two more are planned (see Table 2). These demonstrate the range of current experience with CCS. In all but two of these projects, the source of the CO_2 is natural gas. CO_2 is separated from the natural gas because some natural gas reservoirs contain too much CO_2 to sell on the open market unless the CO_2 is removed first. Motivation for injecting CO_2 underground, in contrast to emitting it to the atmosphere, was a $50 per ton CO_2 emission tax, in the case of Norway, and good environmental stewardship in the others. In addition to these projects, which were developed for the specific purpose of CCS, about 20 million tons per year of CO_2 is injected annually to recover oil from over 50 oil fields, primarily from carbonate formations in West Texas.

All the CO_2 storage projects listed in Table 2 are being used to one degree or another as demonstration projects. International teams of scientists, funded by private and government sources, are deploying monitoring technologies, computer simulation models and risk assessment methods to assess the safety of these projects, improve our understanding of geologic storage and develop advanced technologies for monitoring CO_2 storage projects. None of these existing projects is as large as would be required to capture and store the 8 million tons per year of CO_2 from a typical 1000 MW coal-fired power plant. However, the scale-up of individual projects ranging from the 1 to 4 million tons per year to 8 million tons per year should be achievable and these projects provide substantial experience on which future projects can build.

Storage Requirements and Capacity

Predicting how much CO_2 needs to be captured and stored in order to stabilize atmospheric CO_2 concentrations at safe levels is very difficult. The large number of variables such as future population growth, world-wide prosperity and standard of living, diffusion of new energy technologies, continued use of fossil fuels, natural carbon cycle dynamics and human behavior all contribute to the uncertainty in predicting CCS requirements. Nevertheless, a number of studies have attempted to address these questions and most agree that trillions of tons of storage could be needed over the next several hundred years. Annual CCS requirements could peak in the range of 10 billion tons of CO_2 per year by the end of the next century.

Table 2. Summary of current and planned CCS projects.[3]

Project (Operator)	**Application**	**Mass of CO_2 Million Tons/yr**	**Capture Technology**	**Storage Formation**
Sleipner, North Sea (Statoil)	Storage of CO_2 stripped from natural gas	1 since 1996	Amine-Scrubber	Off-shore salt-water sand formation
Weyburn, Canada (Encana)	EOR and CO_2 storage from coal gasification	1.7 since 2000	Pre-combustion Gasification	On-shore oil reservoir in carbonate rock
In Salah, Algeria (BP)	Storage of CO_2 stripped from natural gas	1 planned for 2004	Amine-Scrubber	On-shore gas reservoir in sandstone
Gorgon, Australia (ChevronTexaco)	Storage of CO_2 stripped from natural gas	4 planned for 2006	Amine-Scrubber	Island salt-water sandstone formation
Snohvit, Off-shore Norway (Statoil)	Storage of CO_2 stripped from natural gas	0.7 planned for 2006	Amine-scrubber	Off-shore salt-water sandstone formation
San Juan Basin, New Mexico (Burlington)	Enhanced coal-bed methane production		Natural CO_2 Source	On-shore coal bed

World-wide, national, and regional estimates of storage capacity have been attempted over the past decade by a number of research groups. Global results are summarized in Table 3. While the range of estimates is large, there is consensus that the largest potential capacity is in deep salt-water filled sandstones in large sedimentary basins. In fact, it is estimated that salt-water filled formations have the capacity to accommodate hundreds of years at current CO_2 emission rates. However, these capacity estimates have not yet been validated by regional or site-specific field experiments. As pointed out by Burruss (2004), better estimates may be available for oil and gas reservoirs. Burruss estimates that depleted oil and gas reservoirs in the U.S. have 40 to 50 years of storage capacity at today's emission rates. Similar conclusions have been drawn for international and regional studies. The limited capacity of oil and gas reservoirs and the lack of co-location with many existing power plants necessitates that rapid progress be made to quantify the capacity and identify suitable storage sites in salt-water filled formations. It is interesting to note that the majority of CCS projects today are in salt-water formations. The lack of nearby sites or infrastructure for EOR and the expediency of using co-located salt-water formations made this the preferable option. Whether this trend is coincidental or a precursor of future choice remains to be seen.

Table 3. Summary of world-wide storage capacity estimates.

Formation Type	Capacity Estimate (Gt CO_2)	Source
Depleted oil and gas reservoirs	~ 450 Gt	Stevens et al., 2001: GHGT 6 pp. 278-283
Coal-bed methane reservoirs	60 - 150 Gt	Stevens et al., 1999: GHGT 5 pp. 175-180
Salt-water filled formations	300 - 10,000 Gt	IEA Greenhouse Gas R&D Programme, 1994

The issue of co-location is an important one and will play a major role in which types of formations are selected for geologic storage. Figure 3 shows the location of the largest CO_2 sources in the U.S. overlain on the distribution of oil and gas reservoirs, deep coal beds and salt-water formations. In some areas, such as the Texas Gulf Coast, the Rocky Mountain Region and the Western United States, oil, gas, and salt-water formations are all available. In the Midwest and northeast, deep salt-water formations are the primary option. If a large interconnected pipeline infrastructure were built to transport CO_2 between regions, co-location of sources and sinks would not be the primary determinant of which type of formation was used for storage. Perhaps more importantly, Burruss (2004, this volume) surmises that eventually, new large power stations will be sited specifically for co-location with attractive storage sites, such as large oil and gas reservoirs. This would require an extensive network of CO_2 transport pipelines, with distances extending up to several thousand miles. While this at first may appear overly ambitious, it is not so unlikely given that today we have over 180,000 miles of natural gas pipelines in the United States[4] and over 1100 miles pipelines transporting CO_2 from the four corners areas into West Texas for CO_2 enhanced oil recovery[5].

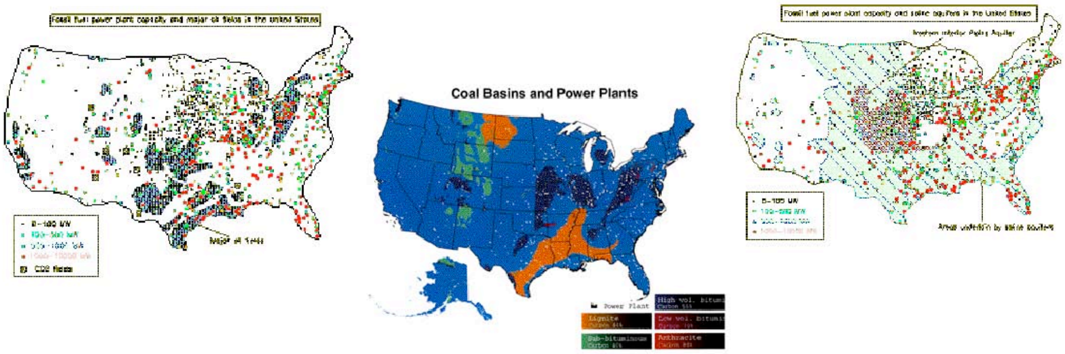

Figure 3. Location of major power sources and potential storage formations.

In summary, current estimates suggest that sufficient storage capacity will be able to accommodate decades, and probably centuries, of anthropogenic CO_2 emissions. Estimates in oil and gas reservoirs are the most reliable – which is fortunate since these may well be the best sites for large scale CCS in the near term. Capacity estimates in salt-water formations are very large but must be validated, in much the same way that "known reserves" are established for oil and gas resources.

Potential Risks to Humans, Resources and the Environment

Carbon dioxide is generally regarded as a safe, non-toxic, inert gas. It is an essential part of the fundamental biological processes of all living things. It does not cause cancer, affect development, or suppress the immune system in humans. However, CO_2 is a physiologically active gas that is integral to both respiration and acid-base balance in all life, and exposure to high concentrations can be harmful and even fatal. Ambient atmospheric concentrations of CO_2 are currently about 370 ppm. Humans can tolerate increased concentrations with no physiological effects for exposures up to 1% CO_2 (10,000 ppm).

Carbon dioxide is used in a wide variety of industries: from chemical manufacture to beverage carbonation and brewing, from enhanced oil recovery to refrigeration, and from fire suppression to inert-atmosphere food preservation. Because of its extensive use and production, the hazards of CO_2 are well known and routinely managed. Engineering and procedural controls are well established for dealing with the hazards of compressed and cryogenic CO_2. Carbon dioxide is regulated by Federal and State authorities for many different purposes, including occupational safety and health, ventilation and indoor air quality, confined-space hazard and fire suppression, as a respiratory gas and food additive. Current occupational safety regulations are adequate for protecting workers at CO_2 separation facilities and geologic storage sites.

The potential public health and environmental risks of CCS are believed to be well understood based on analogous experience from the oil and gas industry, natural gas storage, and the EPA's Underground Injection Control Program. For CCS, the highest probability risks are associated with leakage from the injection well itself, abandoned wells that provide short-circuits to the surface and inadequate characterization of the storage site—leading to smaller than expected storage capacity or leakage into shallower geologic formations. Potential consequences from failed storage projects include leakage from the storage formation, CO_2 releases back into the atmosphere, groundwater and ecosystem damage. Avoiding these consequences will require careful site selection, environmental monitoring and effective regulatory oversight. Fortunately, for the highest probability risks, that is, damage to an injection well or leakage up an abandoned well, methods are available to avoid and remedy these problems. In fact, many of risks are well understood based on the analogous experience listed above, and over time, practices and regulations have been put in place to ensure that most of these industrial analogues can be carried out safely.

To summarize, implemented on a small scale, in a well characterized geologic setting, geologic storage poses no unique or poorly understood risks. However, after the best characterized sites are utilized, significant characterization and risk assessment effort will be needed to accommodate additional CO_2 storage. Burruss (2004) estimates that 0.5 GtC per year (current annual emissions from electrical generations in the United States) could be stored in depleted oil and gas reservoirs for the next 50 years before the capacity is depleted. Similar or even greater amounts of CO_2 could be stored in salt-water filled formations that are shown to have high quality seals during this period. During the early phases of implementing CCS, additional sites that are less well characterized can be evaluated to establish "proven" storage reserves.

Monitoring and Verification of CCS Projects

Ensuring that CCS is safe and effective will require regulatory oversight, careful management of site selection and acquisition of monitoring data, and verification of CO_2 emission reductions. Credible monitoring and verification may well be the single-most important means of gaining public acceptance for geologic storage of CO_2. Five primary types of measurements provide the foundation for monitoring and verification of CCS:

- Measurement of CO_2 concentrations in the workplace (separation facility and wellfield) to ensure worker and public safety;
- Measurement of emissions from the capture system and surface facilities to verify emission reductions;
- Measurement of CO_2 injection rates, which are used to determine how much CO_2 has been injected into the underground formation – if enhanced oil recovery is taking place concurrent to CO_2 storage, any CO_2 produced with the oil must be monitored to calculate the net storage;
- Measurement of the condition of the well using well logs and wellhead pressure measurements; and
- Measurement of the location of the plume of CO_2 as it fills up the storage formation. This type of measurement can also be used as an early warning system in the event that CO_2 is leaking out of the storage reservoir.

It is also possible to measure surface fluxes of CO_2 using methods developed for studying the natural cycling of CO_2 between the atmosphere and the Earth's surface, but these measurements may not be used routinely due to the very low probability that CO_2 would be released back into the atmosphere from the storage reservoir. Nevertheless, they are available and have sufficient sensitivity to detect CO_2 leaks in that the event that they reach the surface. Deploying surface flux monitoring may be helpful in building public confidence in CO_2 storage.

Of the five monitoring requirements listed above, the first four are very well developed because the measurement technology can be borrowed directly from a variety of other applications, including electrical generation plants, the oil and gas industry, natural gas storage, disposal of liquid and hazardous waste in deep geologic formations, groundwater monitoring, food preservation and beverage industries, fire suppression and ecosystem research.

The fifth, monitoring plume migration, is somewhat more challenging because the sensitivity and resolution of existing measurement techniques need to be evaluated and perhaps improved. In addition, certain types of plumes, namely, narrow vertical plumes of rising CO_2 may be difficult to detect (Myer, 2003). Today, seismic imaging is the primary method for monitoring migration of CO_2 plumes in geologic storage projects. Seismic imaging technology was developed for oil and gas exploration and more recently, application has been extended to track CO_2 migration. When repeated on a periodic basis, differences in the images can be used to detect the location of CO_2. Seismic imaging is similar to the technology used to generate sonograms for medical applications, but carried out on a much larger scale. Other techniques such as electromagnetic and gravitational measurements have lower sensitivity and resolution, but may be used in combination with seismic techniques to fine-tune the interpretation of the data or in the interim between seismic measurements. Seismic imaging (see Figure 4) has been very successful for monitoring the location of the CO_2 plume at the Sleipner West project in the North Sea. Although seismic imaging has been used very successfully at Sleipner, more studies are needed in a wide variety of geologic settings to demonstrate that this technology has widespread applicability.

Because monitoring and verification of geologic storage is likely to be very important for gaining public acceptance of CCS, research and demonstration in this area is a very high priority. Pilot projects, ranging from small to large scales, are needed to demonstrate the accuracy, reliability and sensitivity of existing techniques. In addition, research is needed to develop new cost effective techniques that may provide even greater levels of assurance. In particular, more methods for providing early warning that a storage project is failing would be valuable. It is also important to conduct these pilot and demonstration projects in a wide variety of geologic settings because the accuracy and sensitivity of monitoring techniques differs in different geologic environments.

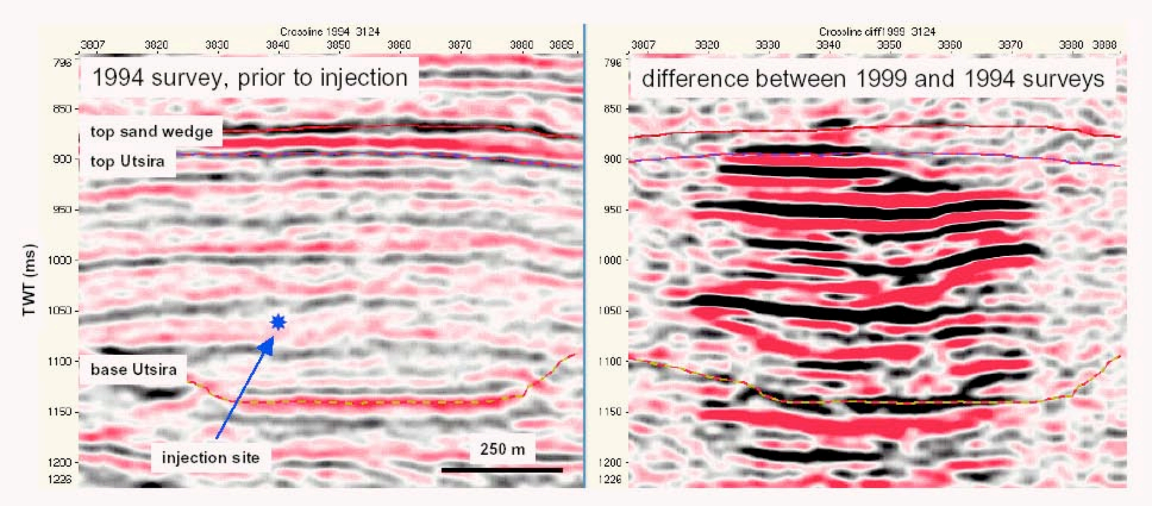

Figure 4. Seismic image of the plume of CO_2 injected into a deep geologic formation below the sea floor in the North Sea (from Zweigel et al, 2001).

Legal and Regulatory Issues

An appropriate legal framework with effective regulatory oversight is a cornerstone of effective CCS. Laws must be in place to protect personal property and the environment, and to assign liability for failed storage projects. Regulations must be in place to select and permit storage sites, specify monitoring and verification requirements, and enable constructive engagement with potentially affected citizens and communities.

The question of permanence of CO_2 storage is one of the key regulatory and performance issues that remains to be answered. Some scientists believe that storage is needed only for several hundred years. The concept of "storage effectiveness" has been developed to quantify how much must remain underground to avoid compromising the effectiveness of geologic storage. Estimates of the required "storage effectiveness" range from about 90% in 100 years to 90% in 10,000 years (Pacala, 2003, Hepple and Benson, 2003; and Lindeberg, 2003). The range is explained by differences in assumptions about how much CO_2 is stored, atmospheric stabilization levels, future industrial emissions, economic considerations about the cost of storage, and the effectiveness of the natural carbon cycle as a CO_2 sink. Other scientists believe that geologic storage will be and should be, for all intents and purposes, "permanent." Preference for this approach is determined in part by national attitudes and partly by the belief that geologic structures could provide storage for millions of years. This author believes that from the perspective of a "climate change technology," a storage effectiveness of 90% in 1000 years is acceptable, and in fact, a conservative lower limit to the performance that is needed. However, the possibility for local groundwater and ecosystem impacts associated with leakage at this rate may argue for more permanent storage. Coming to consensus on the performance requirements, including the question of permanence, for geologic storage is an important issue that must be addressed.

There is also no consensus on whether or not adequate regulations are in place for oversight of geologic storage. Certainly, many of the building blocks are in place. Some would argue that existing regulations for CO_2 injection during enhanced oil recovery are adequate. Others would say that the EPA's Underground Injection Control Program, which regulates underground disposal of hazardous wastes, is sufficient. Others, like this author, believe that CCS is sufficiently unique and may be implemented on such a large scale to warrant its own regulatory regime. Chief among the arguments for this include the unique physical and geochemical attributes of CO_2 and the long-term storage requirement. At low concentrations, CO_2 is not hazardous and in fact essential for life, so a set of regulations based on substances that are hazardous at parts-per-billion concentrations make no sense. Similarly, injection of CO_2 for enhanced oil recovery has no requirement for long-term storage, so existing regulations provide little assurance that CO_2 would be safely stored for thousands of years or longer.

Getting started on developing a science-based regulatory approach for CCS is needed soon to allow regulatory permitting of upcoming experimental projects and begin to define a set of performance requirements against which projects can be objectively assessed.

Cost of CO_2 Capture and Storage

Currently, the high cost of CCS appears to be the largest barrier to implementation. Estimated costs for CCS range from \$30 to \$70 per tonne CO_2 depending mainly on the capture technology and concentration of CO_2 in the stream from which it is captured (Rubin and Rao, 2003). While this metric may be useful for comparing the cost of CCS with other methods of reducing CO_2 emissions, the increase in costs of electrical generation may be a more meaningful economic metric because the electrical generation sector will provide the biggest benefit from CCS.

Simbeck (2004) calculates that CO_2 capture (separation and compression) alone will increase the cost of electricity from \$43 per MWh to \$61-\$78 per MWh for new power plants and from \$17 per MWh to \$58-\$67 per MWh for existing coal plants that have already been paid off. Separation and compression typically account for over 75% of the costs of CCS, with the remaining costs attributed to transportation and underground storage. Pipeline transportation costs are highly site-specific; they depend strongly on economy of scale and pipeline length. Costs of underground storage are estimated from \$3 to \$10 per tonne CO_2.

In addition to the high cost of CCS, the “energy penalty” for capture and compression is high. The post-combustion, “end-of-pipe” capture technologies use up to 30% of the total energy produced, thus dramatically decreasing the overall efficiency of the power plant. Oxy-combustion, because it requires separation of a pure source of oxygen from air, also has a similarly high energy penalty, although eventually, new materials may off-set the energy penalty by allowing for higher temperature and consequently more efficient combustion. Pre-combustion technologies have the potential to lower energy penalties to the range of 10 to 20%, leading to higher overall efficiency and lower capture costs.

Public and privately sponsored research and development programs are aggressively trying to lower the costs of CO_2 capture. One industrial consortium, the CO_2 Capture Project, has the goal of reducing capture costs by 50% below today’s baseline. Early studies in pre-, post- and oxy-combustion have all shown promise to meet the target cost reduction[6]. The U.S. Department of Energy has a cost goal of \$10 per ton CO_2. This extremely challenging target is likely to be hard to meet without significant advances in separation technology, including membrane separators and new absorbents. Outreach efforts by the Department of Energy and the National Academy of Sciences are tying to engage academic researchers with new ideas in these areas. Clearly achieving these cost reduction goals would significantly increase the probability that CCS would become a major element of our climate change technology strategy.

Establishing the viability of CCS will require a significant investment in research and demonstration projects. This author agrees with Davis (2004) who states:

> *“... four to six such demonstrations will be required, focusing on the technical issues outlined above and testing the concept in numerous operating locations. Because of the long project lead times, and the costs associated with these activities, it is imperative that these activities are*

> *coordinated internationally, with appropriate sharing of the findings to address public concerns about the technology."*

FutureGen, the U.S. Department of Energy's flagship demonstration project for a next generation coal-fired power plant that co-produces electricity and hydrogen for transportation, is estimated to cost $1 billion dollars over a ten-year period. Assessing the viability of CCS as an option for a low-carbon future could require from four to six such demonstrations around the world at a total cost on the order of $5 billion dollars over a ten to twenty year period. Clearly international cooperation and cost-sharing between the public and private sector would greatly improve the viability and expedite initiation of these demonstration projects.

However, it is possible to significantly accelerate some of the demonstration projects and lower costs by focusing only on geologic storage, with the rational that unlike power generation and separation technology, geologic storage is highly site-specific and therefore requires multiple demonstration projects. Costs for these demonstration projects could be lowered by using existing sources of CO_2, such as from petroleum refineries or ammonia production plants that do not require costly separation. The costs for a large-scale, ten-year demonstration project would be on the order of $200 million. This expedited approach has the benefit that the projects could begin as soon as the sites were selected and the permits obtained. The combined benefits of lower overall costs and expedited assessment of geologic storage argue in favor of choosing to focus some demonstration projects exclusively on geologic storage. Four to six full scale demonstrations projects could be carried out in the United States at a cost of approximately $1 billion. Moreover, while lowering the cost of separation may be technologically more challenging, public acceptance of geologic storage may ultimately be the bigger obstacle to the viability of CCS. Again, this argues for an expedited assessment of geologic storage, carried out in parallel to full-scale demonstration of CCS technology.

Public Acceptance

CCS is a very new technology that is only now beginning to be known to the public. Over the past several years, popular science journals have published a handful of papers on the subject. Major newspapers and widely circulated news magazines have written short articles describing the concept, generally favorably, or at least with an open mind. As more people are exposed to the idea of CCS, public opinion will be shaped, but it is fair to say for now, that the public is generally not aware of the concept and have yet to form an opinion. Most likely, public debate about CCS will take place in three important forums.

First, as the United States continues to shape and refine its climate policy, CCS will retain a prominent role in the strategy, raising national awareness of the issue. Issues about economic competitiveness, international trade, policy implements and timing are likely to dominate this debate.

Second, non-governmental organizations (NGOs) with an interest in environmental policy will monitor and continue to evolve their opinions on whether or not CCS should play an important role in a low-carbon future. Key to these discussions will be possible preferences for energy efficiency and renewable energy over CCS as the optimal climate change technology policy. Any technology that prolongs the use of fossil fuels, such as CCS, may be viewed skeptically. In addition, the energy penalty for capture, particularly of post-combustion capture, may be viewed as wasteful and undesirable. Risks of local and regional environmental impacts and our ability to anticipate and avoid them will be crucial. As implementation become more imminent, the public debate will intensify and NGO's will play an important role in shaping public opinion about the relative benefits and risks of CCS.

Finally, and perhaps most importantly, on-the-ground pilot and demonstration projects will draw the interest and concern of the neighboring communities. Concerns about human safety and environmental impacts, property values, mineral and water rights will probably dominate these debates, which may be tempered in some areas, particularly where enhanced oil recovery is possible, by job opportunities, financial compensation and economic growth. Pipeline construction, particularly in new areas will also be met with these concerns.

How these three debates individually and collectively transpire will be critically important in determining whether CCS will gain public acceptance. The public must be persuaded that CCS is needed, and assured that it can be safe and effective. Laws and regulations that protect the public and the environment are critical to the success of CCS. The lack of public acceptance could become the major barrier to CCS.

Conclusions

CCS is in practice today and more is planned. Significant benefits from this approach include the ability to continue to use the plentiful and low cost fossil fuel resources that are available today – while at the same time, building a smooth economic transition to a low-carbon future. CCS builds upon a technology base developed over more than half a century by the oil and gas industry. Consequently, it is being implemented in some situations today, but significant technological improvements and cost reductions are also on the horizon, which can lead to even broader application.

Yet today, significant barriers to large-scale implementation of CCS remain. This challenge is best put into context by considering the scale of the endeavor. Imagine that by the year 2050 world-wide we will potentially need thousands of CCS projects that are each as big or bigger than the Sleipner Project. In the United States alone, CCS for our 2 billion tons of CO_2 emissions from electrical generation from fossil fuels could require 200 projects, each 10 times larger than the Sleipner project.

To support an endeavor of this scale, numerous advances are needed. Technological innovations are needed to reduce the cost of capture – better separation technologies, technological advances in turbine design to support repowering with advanced generation systems and systems optimization. Widespread use of CCS will also require large investments by the private sector and institutional commitments on the part of the government. New infrastructure is needed, both for CO_2 transportation and power generation. Retrofit of existing coal-fired plants may not be economical and CCS may need to await replacement of existing generation capacity with new plants that more efficiently capture CO_2. Research is needed to prove that the potentially huge storage capacity of salt-water filled formations can be used to safely and effectively store CO_2 for thousands of years or longer. Institutional issues such as regulatory oversight and the legal framework for CCS needs must be addressed. Key to these institutional issues is recognition and resolution of the intergenerational commitments inherent in underground geological storage of CO_2. Questions such as "Who is responsible for long-term monitoring?" and "Who is liable for the consequences and remedy should a storage project leak long into the future?" must be answered.

Today, the most significant barriers for implementing CCS are:

- High costs and energy penalties of post-combustion capture and separation;
- High capital costs of gasification re-powering and lack of experience of the electrical generation sector with gasification;
- Limited experience with large-scale geologic storage, including "proving" the estimates of storage capacity in salt-water formations;
- Uncertainty about public acceptance for CO_2 storage in geologic formations, including resistance to CCS based on preference for energy efficiency and renewables;
- Lack of appropriate legal and regulatory frameworks to support widespread application of CCS; and
- Lack of financial resources to support projects of sufficiently large scale to evaluate the viability of CCS.

Overcoming these barriers will require a concerted and persistent effort over the coming decades. Table 4 provides a roadmap of actions required over the near, mid and long-term based on assessments carried out over the past several years, including those studies cited by Davis (2004). These are achievable goals. Efforts have been initiated to address the actions listed in Table 4 by governments and several industrial consortia, but much more is needed. Success can be only assured by a sustained commitment to an adequate program of research and demonstration. In the near term, the estimated cost for achieving these goals is on the order of several billion dollars. Shared between the public and private sector, with close international cooperation to leverage R&D investments, this is a reasonable investment to develop this important option for creating a low-carbon future.

However, we must be mindful that CCS is just one of a number of options that can be used to reduce greenhouse gas emissions. End-use energy efficiency, renewable energy such as solar, hydropower, wind, biomass, and geothermal all have an important role to play. In the end, market forces should play a central role in developing the most cost-effective climate change technologies. By absorbing the cost of CO_2 emission control into the use of fossil fuels, the playing field is leveled for other energy technologies and may in fact be a boon to these alternative energy sources. No matter which path we take in the end, we must now develop a reliable and realistic portfolio of options to reduce atmospheric emissions of CO_2.

Table 4. Near, mid and long term actions needed to enable assessment and deployment of CCS as a major strategy to achieve a low-carbon future.

Near Term (0-10 years)	Mid-Term (10 to 30 years)	Long Term (> 50 years)
• Research to bring down CCS costs and develop greater assurance about the security of geologic storage • Policies that discourage continued use of existing electrical generation capacity without CO_2 controls • Demonstration of coal gasification combined with CCS • Demonstrations of geological storage at 4 to 6 sites in different geologic settings • Development of science-based regulatory approach that addresses site selection, risk assessment and long term monitoring, and clearly addresses local, regional, and NGO safety and environmental concerns	• Assessment of regional "proven" storage reserves • Research and development to improve the performance of capture systems and optimize storage in geologic formations • Policies that encourage use of low-carbon power generation technologies • Deployment of full scale CCS projects at new or repowered electricity plants with incentives to make these "show-case" projects that are highly visible and transparent to the public • Research and demonstration projects to develop hydrogen-based transportation systems • Refinement of regulatory approaches to take advantage of "learning by doing"	• Full-scale deployment of hydrogen-based transportation systems from fossil-fuels generated hydrogen • Development of large-scale infrastructure to support widespread use of CCS for both the electricity and transportation sectors • Refinement of regulatory approaches to take advantage of "learning by doing"

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[1] Evaporites are sedimentary rocks that consist of salts formed by precipitation in closed water basins. They often have very low permeability and form seals for oil and gas reservoirs. Examples include sodium chloride, gypsum, anhydrite, limestone and dolomite.

[2] From 2000 to 2003 the United States Department of Energy sponsored an international code intercomparison study with participation of ten scientific teams from six different countries. The teams conducted computer simulations of seven different problems that tested the ability to simulate the physical, chemical and mechanical processes that are important for secure geologic storage of CO_2 (www-esd.lbl.gov/GEOSEQ/).

[3] Most of the experience in CCS has come from separating CO_2 from natural gas. While the experience gained on geologic storage is relevant to storage of CO_2 from electrical generation, the experience with separation is less relevant because separation of CO_2 from flue gas is more challenging than for separation from natural gas.

[4] See www.ingaa.org for a description of the natural gas transport infrastructure in the United States and the safety regulations that are used to protect public and worker safety.

[5] See www.kindermorgan.com for more information about CO_2 production from the McElmo dome and pipeline transport to West Texas for CO_2 enhanced EOR.

[6] Studies of post-combustion, pre-combustion and oxygen combustion all have shown promise for achieving target cost reductions. Follow-on experiments and studies will be needed to confirm these promising results. See www.co2captureproject.org for more information about these studies.

Pew Center/NCEP 10-50 Workshop

Contributing Paper: CO_2 Capture Economics

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I. Introduction

CO_2 emissions from fossil fuel use are the principal man-made source of greenhouse gas emissions. Since the industrial revolution in the early 1800s, atmospheric CO_2 concentration has increased over 33% and this is accelerating with increasing fossil fuel use.

This analysis of CO_2 capture economics addresses reduction of carbon emissions while continuing to use carbon based fossil fuels. This could become an important option as energy intensity reductions (conservation and increased efficiency) reach their practical economic limits, and until it becomes economic to use renewables (wind, solar, nuclear) to satisfy most of our energy needs.

The economics of CO_2 capture, transportation and geologic storage favor utilization of very large "point sources" of man-made CO_2 emissions. Consequently this option is most appropriate for fossil fuel based power generation, especially coal-based power plants due to their traditional large sizes and very high CO_2 emissions per MWh of net power generated

II. CO_2 Capture Options and Basic Issues

There are only 3 general types of CO_2 capture technology:

1. Post-combustion
2. Oxygen-combustion
3. Pre-combustion

Post-combustion capture involves scrubbing CO_2 out of flue gas after the fossil fuel is combusted. This flue gas is usually at atmospheric pressure with a low concentration (5-15%) of CO_2 due to all the nitrogen in the air used for combustion. There are also small amounts of excess oxygen and sometimes of sulfur dioxide (SO_2) and nitrogen oxides (NO_x). These factors increase the cost and energy requirements of post-combustion CO_2 capture. CO_2 capture at these low CO_2 concentrations and system pressure thereby very low CO2 "partial pressure" (defined as concentration times system pressure) usually involves reversible chemical reactions which require heat in order to regenerate and recycle the chemicals used to capture the CO_2, known as absorbents. The most common technology for capture uses a chemical amine solution to absorb the CO_2, the CO_2 subsequently being released from the solution by heating it. The large size of the post-combustion absorbers, large absorbent circulation rates and especially the high regeneration heat requirement result in high costs for post-combustion CO_2 capture. This option is generally considered for existing boiler systems, especially when the flue gas is low in SO_2

and NO_x due to clean natural gas being used for combustion, or for flue gas from coal boilers that already have FGD (flue gas desulphurization) and SCR (selective catalytic reduction) systems that remove these gases. The large steam requirements of the amine stripper plus the power requirements of the CO_2 compressor (needed to deliver the CO_2 to pipelines) lead to a significant drop in net capacity and efficiency. This loss in net capacity and efficiency is usually in the range of 25-30% relative to the same combustion system without CO2 capture. Furthermore, post-combustion CO_2 capture has only been demonstrated at a relatively small scale.

Oxygen-combustion involves using pure oxygen in place of air for combustion thereby producing a flue gas of mostly CO_2 and water vapor and resulting in higher concentrations of CO_2 but usually at low pressure. The oxygen is obtained by separating it from air prior to using it to burn the fuel. Retrofitting existing boilers for oxygen-combustion usually requires recycling some flue gas CO_2 to the combustion chamber in order to control the high temperatures characteristic of oxygen combustion. Some new advanced systems try to control the high oxygen-combustion temperature with water injection in place of recycling CO_2. The high capital costs and large power requirements of air separation to make oxygen are the key contributor to the high cost of this approach. This option is generally considered for existing coal boilers which do not have any SO_2 and NO_x control, in the hope that these pollutants can be captured and disposed of with the CO_2. However, physical properties of gaseous SO_2 and NO_x with supercritical (liquid-like) CO_2 at high pressure may require their removal from the CO_2 to avoid two-phase flow (liquid and gas mixture) that would make pumping and pipeline transportation more difficult. The large power requirements for oxygen production plus that of the CO_2 compressor power leads to a significant drop in net capacity and efficiency. This loss in net capacity and efficiency is usually in the range of 25-30% relative to the same combustion system without CO_2 capture. Furthermore, oxygen combustion for CO_2 capture as only been tested at very small-scale pilot plants.

Pre-combustion capture involves converting a fossil fuel into hydrogen (H_2) and CO_2 usually via gasification. Electricity is then generated by combusting hydrogen in a gas turbine and further efficiencies are gained by using waste heat to power a steam turbine. Oxygen is generally used for combustion in gasification systems, but compared to oxygen-combustion of pulverized coal, gasification requires significantly less oxygen per unit of fuel feedstock or net power output. Furthermore, when CO_2 is captured via pre-combustion, the CO_2 is at very high partial pressure (high system pressures times the high concentrations). These are critical issues because they greatly reduce the capital costs of the CO_2 absorber, the rate of absorbent circulation, and especially the energy requirements for absorbent regeneration. In fact, processes that use physical solvents rather than chemical absorbents become effective at the high CO_2 partial pressures of gasification. This enables CO_2 recovery in a dry condition, at moderate pressure and little or no use of steam, significantly reducing the CO_2 compressor capital and power requirements, and resulting in a noticeably smaller loss of net capacity and efficiency than post-combustion and oxygen-combustion. An added advantage of pre-combustion CO_2 capture is that it involves production of hydrogen giving it strategic flexibility for future energy trends such as fuel cells and potentially the "hydrogen economy". The key issues impeding deployment of pre-combustion CO_2 capture is that gasification is a complex chemical process in comparison to more familiar, mechanical, steam boiler technologies; and it can be both more expensive and less reliable than traditional steam boiler power plants. Although gasification of fossil fuels to H_2 with CO_2 capture is commercially used throughout the ammonia and oil industries, it is foreign to the power industry, which is also a factor leading to electric utility skepticism and hesitancy.

III. Present Economics of CO_2 Capture in Electric Power Generation

The most important issue when considering CO_2 capture as an option in electric power generation is the increase in price of electricity associated with the cost of CO_2 capture. Calculating an increase requires that a baseline cost of traditional fossil fuel power generation without CO_2 capture be established. Furthermore, retrofits of existing fossil power plants will usually have a loss in net power output unless additional fuel is consumed to meet the energy demands of CO_2 capture and compression.

For new power plants, the most appropriate baseline is the cost of electricity from new state-of-the-art NGCC (natural gas combined cycle) plants which have CO_2 emissions of about 0.34 metric ton CO_2 per MWh. For existing power plants, a typical 20-25 year-old pulverized coal (PC) unit is used to establish baseline costs as this type of unit is responsible for most of the U.S. power industry's CO_2 emissions and almost 10% of global man-made CO_2 emissions. Since these old PC units have amortized (paid-off) most of their original capital costs, the costs of electric power ($/MWh) are low, in the range of only $10-20/MWh or 1-2 cents per kWh. Old PC units have relatively low thermal efficiency which, together with the fact that coal has a higher carbon content per unit of energy than natural gas, results in emissions of about 0.91 metric tons CO_2 per MWh.

Table 1 summarizes the costs of electric power for natural gas and coal with and without CO_2 capture for new power plants. Electric power costs increase from about $43/MWh with no CO_2 control to $61-79/MWh with control depending on the option. These power costs are at the power plants gate and do not include additional power transmission and distribution costs. The costs of CO_2 avoidance range from $67-190/ton CO_2. CO_2 avoidance cost (in $/ton) is defined as the increase in electricity cost (in $/MWh) between a base case and a specific CO_2 capture option, divided by the reduction in CO_2 emitted to the atmosphere (in tons CO_2/MWh) for the same two cases.

Table 1. Costs of Carbon Capture compared to Base Cases

Type of Plant	Capital cost $/kW	Electricity Cost $/MWh	Difference $/kW	Difference $/MWh
NGCC: no CO_2 control	506	42.8		
NGCC: with control	*1,057*	*66.0*	551	23.1
CGCC: no CO_2 control	1,376	45.5		
CGCC with CO_2 control	*1,807*	*61.4*	431	15.9
New PC: no CO_2 control	1,276	42.8		
New PC: with CO_2 control	*2,351*	*78.7*	1,075	36.0

Note: Costs shown in italics are costs with CO_2 control. Assumptions: Coal price is $1.00 per MM Btu HHV; Gas price is $4.30 per MM Btu HHV; plants operate at 80% annual load and capital cost amortization is 15% /yr.

Table 2 compares the costs of electric power from existing mostly paid-off coal fired power plants to the costs of electric power under various CO_2 reduction options. The electric power costs increase from about \$17/MWh to \$58-65/MWh depending on the CO_2 reduction options. The costs of CO_2 avoidance ranged for \$55-165/ton CO_2.

Table 2. Costs compared to old PC plants

Type of Plant	Capital Cost $/kW	Electricity Cost $/MWh
Base Case: old PC	102	17.7
NGCC with control	*1,151*	*65.3*
CGCC with control	*1,687*	*58.4*
PC retrofit (O_2 firing)	*1,119*	*58.9*
PC (scrubbers)	*1,101*	*66.7*

Note: Capital costs shown in Table 2 differ from those shown in Table 1 because parts of the existing facilities can be reused in the retrofit.

IV. Challenges to Adoption of Carbon Capture Technologies

There are 3 basic barriers to CO_2 capture in fossil-fuel based electric power generation:

1. The high costs of capital and electricity, especially relative to continued life extension of our large fleet of cheap paid-off existing coal-fired power plants.
2. Government policies which continue to provide economic incentives to continued life extension of old existing coal-fired power plants
3. The need for successful full-scale regional demonstrations to convince the power industry that massive amounts of CO_2 can be effectively captured and geologically stored for hundreds of years at sites near power plants.

Currently the large fleet of old coal-fired power plants represents about 40% of the entire United States and 10% of worldwide man-made CO_2 emissions. The average age of this 300,000 MW of existing coal capacity is 31 years (MW weighted). Thus there is a large opportunity for CO_2 capture and reductions as this old capacity is replaced.

Recent changes in the Clean Air Act (CCT) and specifically the New Source Reviews (NSR) makes it easier to refurbish existing coal-fired power plants without emission reductions for another 8-10 years. This economically encourages continued life extensions of the over 300,000 MW of old and relatively inefficient coal-fired power plants.

Over the next 10 years, EIA projects power generation CO_2 emissions will significantly increase mostly due to increased use of the existing coal power plant capacity. Government policy changes would be required to discourage this. Economic analysis shows a carbon tax would have little impact because the existing paid-off coal-powered plants have such low costs that it would be cheaper to pay the tax than build replacement plants with low CO_2 emissions.

Over the next 10 years, the best opportunity for advancing CO_2 capture is to support and encourage a number of regional, large-scale, CO_2 capture and storage demonstrations at fossil-fuel power plants. Demonstrations involving retrofits of natural gas plants or coal gasification repowering (i.e. on-site replacement of pulverized coal combustion plants with gasification systems) of existing very old coal plants are likely to be the best options. These approaches avoid the large capacity and efficiency losses that attend retrofits using flue gas CO_2 scrubbers or oxygen-combustion. If a carbon-constrained world develops, natural gas prices are likely to increase. Therefore, coal gasification repowering is likely to prove the more important option.

Coal gasification demonstration with CO_2 capture will also help the traditional coal-based utilities get over their fears and concerns about gasification. Specifically they must realize gasification is a complex chemical process, requiring chemical and oil industry skills to be successful, and they must have opportunities to become acquainted with these processes and skills. There are currently over 20 commercial gasification plants, which make ammonia and pure hydrogen and capture CO_2. Furthermore, General Electric gas turbines have over 450,000 hours of successful operating experience using hydrogen-rich fuel gas. The only issue should be costs, which can be addressed through experience. Electric utility experience, albeit with a much simpler chemical process (flue gas desulfurization), has demonstrated significant cost reductions and improved reliability over the last 20 years through "learning by doing".

The 20-30 year time frame will be the critical period for CO_2 capture. In this time frame most of the large fleet of existing coal power plants in the United States will need to be replaced. Therefore, it is essential that CO_2 capture and storage technologies have been fully and successfully proven before these replacements begin. The additional cost and performance improvements associated with advancing technologies and "learning by doing" in the demonstrated plant over the next 10-20 years will be critical to achieving this goal.

Our ability to accurately predict technological change 50 years out is terrible. Nevertheless, there are several important technical and economic issues to consider relative to CO_2 capture. Existing coal fired power plants are the largest source of CO_2 emissions and are key large "point sources" for effective large scale CO_2 capture. Furthermore, the large reserves and low cost of coal will likely assure its continued use 50 years from now. The two dominant consuming countries of coal will likely remain the United States and China. China's massive growth in coal-based electric power generation is generally following that of the United States but it is about 20-30 years behind. This means that 50 years from now China will have a massive fleet of old paid-off coal fired power plants that will need to be replaced. The United States has the opportunity during the next 10-30 years to develop and demonstrate the best technical and economic options for CO_2 capture from coal-based power plants both for U.S. needs in the 20-30 year time-frame and for China's needs in the 50 year time-frame.

Pew Center/NCEP 10-50 Workshop

Contributing Paper: Gasification and Carbon Capture and Storage: The Path Forward

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I. Introduction

The ultimate objective of the United Nations Framework Convention on Climate Change is to stabilize atmospheric concentrations of greenhouse gases (GHG) at a level that prevents dangerous anthropogenic interference with the earth's climate system. To achieve this objective, it will be necessary for net anthropogenic emissions of GHG to ultimately fall to near zero. Technologies that permanently dispose of fossil fuel emissions will be critical to our ability to address the challenges of climate change.

Coal accounts for approximately 38% of fossil fuel CO_2 emissions. Internationally, it is the most abundant energy resource, and is widely dispersed and available at low cost. Coal plays an important role in the energy portfolio of both developed and developing economies. Two technologies are central to carbon capture and sequestration (CCS) of CO_2 emissions from fossil fuels. Gasification extracts energy from coal in a gaseous form (syngas), from which a high purity stream of CO_2 can be captured and permanently stored in deep underground formations. This is known as geological sequestration.

Both gasification and CO_2 injection into the subsurface are widely used technologies. Gasification has a thirty-year history in the chemical and petroleum industries, where it has an installed base of over 60 GW of syngas. Many of these applications involve the conversion of the syngas into hydrogen. In fact, a key advantage of gasification and geological sequestration is that the production of hydrogen is implicit in the process, and the technologies are therefore key links in not only establishing the security of future energy supplies, but also to the emergent hydrogen energy future. A number of researchers believe that coal gasification with geological sequestration will be one of the lowest cost sources of emissions-free hydrogen.

Underground storage of CO_2 is technically feasible and applicable at scale to the disposal of CO_2 from power stations – all the component technologies are commercially available and widely used. Naturally occurring underground reservoirs demonstrate that CO_2 is retained in favourable geology for millions of years. Currently, 20 Mt of CO_2 are used annually for enhanced oil recovery in the United States (via injection in depleted oil and gas fields), being pumped to injection points through more than 2,000 km of pipelines.

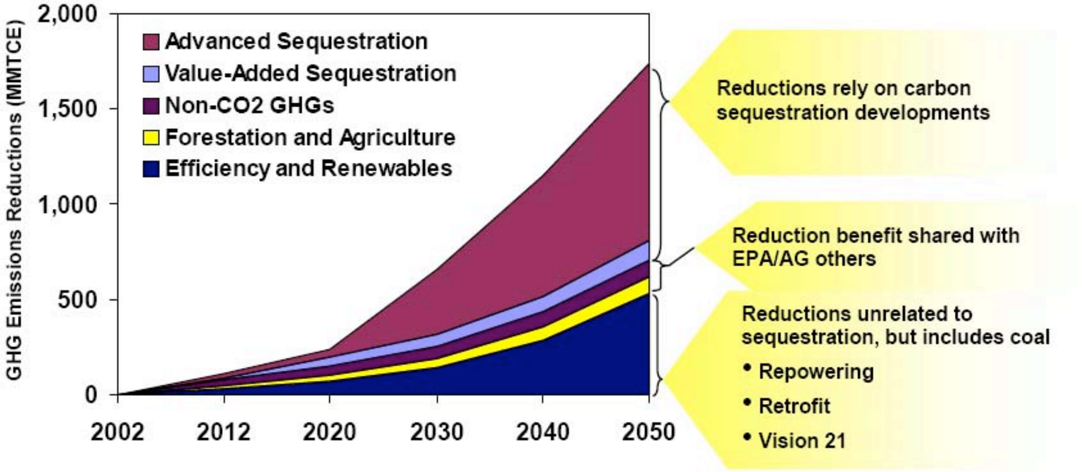
The gasification of coal and capture, transport and underground injection of CO_2 are therefore available and mature technologies. While gasification technologies are currently more expensive than conventional power generation technologies, experience has shown that additional installations will substantially reduce the capital costs. Thus, we need to better understand the costs associated with implementing these technologies at commercial scale.

In addition, geologic sequestration needs to be demonstrated at utility scale, utilizing a variety of geologic formations, to demonstrate its viability as a policy option.

II. Technology Roadmaps

The most complete currently available technology roadmaps for gasification and CCS have been developed in the US and Japan. These roadmaps align well against each other and a range of more recent studies by bodies such the WCI and the Canadian Clean Power Coalition.

The figure below (DoE, 2003) is typical of the projected implementations for advanced sequestration technologies. Up to ~ 2020 the emphasis is on demonstration projects, with commercial implementation occurring after this time.



From "Carbon Sequestration: Technology Roadmap and Program Plan" US DoE NETL Report, 3-2003[1,2,3]

The DoE roadmap indicates the following timetable:

To 2012

- Conduct R&D to enable geosequestration at <US$10/ton carbon
- Commence demonstration of geosequestration at > 1 million tonnes per annum (Mtpa) CO_2,[4] including 4-6 large-scale international demonstration projects
- Develop instruments and protocols for the measurement, monitoring and verification (MMV) of carbon storage

To 2020

- Commercial deployment of carbon capture and storage at no net increase in costs

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[1] "Value-added" sequestration refers to enhanced oil recovery (EOR) and enhanced coal bed methane (ECBM)

[2] "Shared reduction benefit" means that the reduction does not come exclusively from utility sector emissions.

[3] Vision 21 is the U.S. Department of Energy initiative to develop pilot IGCC and CCS projects

[4] This is the minimum scale of injection generally considered necessary to adequately stress the host geology in a way that demonstrates the viability of geosequestration at utility scale.

Post 2020

- Increasing commercial deployment

The Japanese development route is essentially similar in the definition of the key technologies and the timetable for their development. By 2020 the Japanese government projects that:

- Gasification will be in commercial use
- Hydrogen production with CO_2 recovery will have been demonstrated
- Fuel cells will have been demonstrated to run on coal-derived hydrogen
- Liquid fuels and chemicals will be routinely produced from coal

As a result, coal gasification becomes a core technology from 2020, with widespread carbon capture and storage and production of hydrogen for fuel cell use.

III. Non-Technical Issues

The issues to be addressed if the technology is to be widely implemented are, however, wider than the technical considerations (such as reducing the costs of CO_2 capture and demonstrating the permanence of storage), and include:

- **Social** – ensuring that CCS is publicly acceptable
- **Legal** – creating appropriate legal frameworks for the storage rights to geological structures below the surface; and
- **Administrative** – ensuring that an international series of demonstrations at scale, drawing on both government and industry support, enables commercialization of CCS technology in an appropriate timeframe.

Much of the debate to date has centered on the technical issues; however it is likely that the social, legal and administrative issues will be at least as complex, and unless properly addressed, have the potential to significantly delay commercial implementation of the technologies.

IV. Demonstrations and International Co-operation

Satisfactorily resolving these issues will only be possible by conducting a series of demonstrations, to address all realistic combinations of capture technologies and storage options.

These activities will be complicated by the required scale: realistic stressing of the host rock geology only occurs at injection rates at or above 1 Mtpa of CO_2, and confirmation of the retention properties of the reservoir requires injection for approximately three to five years, with monitoring continuing for some years after this.

Demonstrations at this scale are however already underway – the Sleipner project in the North Sea has been operating since 1996, injecting one million tonnes of CO_2 annually; and the U.S.-

Canadian Weyburn project has been recovering CO_2 from the North Dakota gasification operation and pipelining it for EOR use in Canada.

However a further four to six such demonstrations will be required, focusing on the technical issues outlined above and testing the concept in numerous operating locations. Because of the long project lead times, and the costs associated with these activities, it is imperative that these activities are co-ordinated internationally, with appropriate sharing of the findings to address public concerns about the technology.

Overall, considerable administrative and political effort will be required to ensure that an international series of demonstrations at scale, drawing on both government and industry support, enables commercialization of CCS technology in an appropriate timeframe.

The necessary R&D and demonstration projects will be most efficiently and cost-effectively handled as an international series of carefully constructed and integrated parallel programs. Obvious questions arise as to how the necessary coordination will occur, how public and private interests will share the project intellectual property, how the coordination agent(s) will be appointed and empowered, and how the necessary long-term RD&D funding commitments can be secured.

International co-operation and a suitable portfolio of demonstration projects is however developing. The significant sequestration demonstrations (Sleipner, Weyburn, Snohvist) report globally through such organizations as the IEA Greenhouse Program. When other projects under development are considered – Al Salah, Gorgon and FutureGen – the emergence of a critical mass of these demonstrations starts to become clear.

At the other end of the scale, small trials to develop MMV techniques are underway in Japan and Texas, and are proposed for Australia.

V. Conclusions

Underground storage of CO_2 is technically feasible and applicable at scale to the disposal of CO_2 from power stations – all the component technologies are commercially available and widely used. Naturally occurring underground reservoirs demonstrate that CO_2 is retained in favorable geology for millions of years.

The issues for the coal and utility sectors are to ensure that the costs of gasification are acceptably low; that geologic sequestration has been demonstrated to be a viable policy option; and that the public, legal and administrative issues around CCS have been addressed.

Pew Center/NCEP 10-50 Workshop

Contributing Paper: Geologic Sequestration of Carbon Dioxide in the Next 10 to 50 Years: An Energy Resource Perspective

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I. Introduction

The three main options for geologic sequestration of carbon dioxide are storage in depleted oil and gas reservoirs, in salt-water formations, and in coalbeds. Benson (this volume) discusses the potential role of geologic sequestration in a portfolio of carbon management options to decrease emissions of carbon dioxide to the atmosphere. Each of the options is currently undergoing field trials ranging in size from a few thousand metric tons of total injected CO_2 to large projects like Sleipner and Weyburn that each inject about one million metric tons of CO_2 per year and will have lifetimes of about 20 years (Benson, Table 2, this volume). The most technologically mature option is injection into depleted oil and gas reservoirs because the oil and gas industry has 25 years experience injecting CO_2 into petroleum reservoirs for enhanced oil recovery (EOR).

The obvious first order question about geologic storage of CO_2 is, do we have enough storage space? Initial, global estimates cited by Benson (this volume, Table 3) certainly suggest that we do, especially when we combine the capacities of all three geologic options. The difficult questions are in the details of implementing geologic sequestration on a national scale. We can estimate the capital costs of carbon capture from existing power plants and from future generations of gasification power stations (Simbeck, 2001, 2003; Simbeck and McDonald, 2001). However if the volume of CO_2 that must be stored is so great that the best long-term storage sites are exhausted in only a few years, the role of geologic sequestration in controlling CO_2 emissions will be limited. The corollaries to the question of total storage volume are 1) how much is enough; 2) what characteristics define the best storage sites; and 3) where are such sites located relative to large CO_2 point sources of emissions. None of these questions is simple to answer.

II. Near Term Storage Requirements in the United States

One way to set a target for storage capacity in the United States is to examine CO_2 emissions from fossil fuel combustion shown in Table 1. The obvious targets for CO_2 capture and storage are the largest stationary sources, coal and natural gas fired electrical generating stations. Total emissions from electrical generation are about 0.5 billion metric tons of carbon (gigatons, Gt(C)) per year, or about 35 trillion cubic feet (TCF) of CO_2 gas. This amount of CO_2, about one-third of total annual U.S. emissions, is about the maximum amount that can be captured from the present energy infrastructure in the U.S. Capture of CO_2 from industrial sources such as gas processing, fertilizer production, cement kilns, and petroleum refineries could eliminate an additional 10% of emissions.

Table 1. U.S. fossil energy production[1] and CO_2 emissions[2], (EIA, 1999)

Energy Source	Total Energy[3] (QBTU)	% Electricity Generation	% Transportation	Carbon (Gt)	CO_2 (Gt)
Natural Gas	22.8	14	3	0.31	1.14
Coal	23.5	82	0	0.54	1.98
Petroleum	37.7	2.7	67	0.64	2.33

[1] Total domestic production plus imports

[2] Emissions are given in units of gigatons (Gt) of carbon and Gt of CO_2. To convert Gt (C) to Gt CO_2, multiply by 3.67. This factor is the ratio of the molecular weight of CO_2 to the atomic weight of carbon and accounts for the additional mass of oxygen in CO_2 compared to the mass of pure carbon. Other conversions that are important for this paper are the volume of CO_2 gas at surface conditions that is equal to 1 metric ton of CO_2, 1 metric ton CO_2 = 18,900 standard cubic feet (SCF), and the fact that at depths in the subsurface of 1.5 to 2.0 km, CO_2 has a liquid-like density such that 1 metric ton has a volume that is equivalent to about 11 barrels of petroleum (at 42 gallons/petroleum barrel).

[3] QBTU = quadrillion British thermal units (10^{15} BTU, commonly called "Quads")

About 40% of current U.S. emissions are from transportation fuels. Emissions from mobile sources cannot be captured and stored with known, practical methods. Therefore, reduction in emissions from transportation will require either more energy efficient vehicles that emit less CO_2 per passenger-mile traveled, or replacement of current technology with hydrogen technology. Most scenarios for hydrogen production are based on large-scale centralized plants that integrate CO_2 capture with hydrogen production and electrical generation either through coal gasification or reforming natural gas (Simbeck, 2003). A transportation system powered by centrally generated hydrogen would allow geologic sequestration of the CO_2 waste stream from hydrogen production.

III. Storage Capacity in a 10 to 50 Year Time Frame

Important questions for large-scale implementation of geologic sequestration of CO_2 are the definition of the "best" sites for geological storage, or definition of the criteria to rank the quality of storage sites, and the aggregate volume of the "best" sites. From the perspective of petroleum geology[1], known petroleum reservoirs are the best near-term storage sites for carbon dioxide. Reservoirs have 3-dimensional closure and a seal. These structures are known to be capable of retaining petroleum (crude oil and natural gas) for millions of years. CO_2 at subsurface pressures and temperatures has physical properties similar to volatile, liquid petroleum, so that CO_2 will fill these structures in much the same way as petroleum has filled reservoirs naturally. Also, CO_2 storage in depleted oil and gas reservoirs allows recovery of residual fossil fuel resources (enhanced oil recovery, EOR) that can be marketed to offset the costs of CO_2 storage. The volume of incremental recovery of oil, in particular, is potentially large, on the order of 10's of billions of barrels of oil, which could offset a fraction of current and future oil imports (Fischer, 1987). Although CO_2 storage integrated with enhanced oil recovery is the most promising route to near-term geologic sequestration of CO_2, storage in gas reservoirs with enhanced recovery of natural gas (Oldenburg, Stevens, and Benson, 2003), and in coals with enhanced coalbed methane recovery (Reeves, 2003) is also possible. Each of these options has the potential for economic returns from resource recovery that can partially offset the costs for sequestration projects.

IV. CO_2 Storage in Petroleum Reservoirs, Saline Formations, and Coalbeds

Carbon dioxide storage in petroleum reservoirs is closely related to storage in saline formations. Most conventional petroleum reservoirs have a base defined by an oil or gas-water contact. The water at the contact is usually the saline formation water (brine) that fills the porosity of geologic formations in the absence of a petroleum accumulation. A petroleum reservoir is commonly a part of a geological formation that can be called a saline formation. The hydrologic properties of the formation that control injection of CO_2 into a petroleum reservoir will apply to injection into adjacent brine formation. The relationship of CO_2 storage in petroleum traps and saline formations is important for assessment purposes because petroleum traps can be considered the "known resource" of CO_2 storage volume in a saline formation. This is the volume that was characterized by geologic and engineering studies undertaken to optimize petroleum production. It is the volume that is most "bankable" from the perspective of a financial analysis of CO_2 storage costs in the near term. In my opinion, it is the volume that is most appropriate for immediate to near-term implementation of CO_2 storage. In the emerging protocols for establishing emissions reduction credits (ERCs), geologic storage in a reservoir of known dimensions and geographic location will aid in establishing and maintaining title to the stored CO_2 and the associated, financially tradable credit.

The potential storage volume of saline formations exceeds other geologic options (Benson, Table 3, this volume). Whether we can actually use all or a large fraction of this volume is unclear. The general trapping mechanism in saline formations is called "hydrodynamic trapping" and is based on the assumption that the flow rate of a separate CO_2 phase in porous media is relatively slow. This then implies that the CO_2 would not return to the surface in times less than 1000's of years. Saline formations may also have low permeability seals that will inhibit vertical migration. However, where saline formations are not petroleum bearing, they are not well characterized at present. Therefore, identification of the best parts of a saline formation for initial, large-scale CO_2 storage projects is difficult. Adequate characterization of porosity, permeability, distribution of seals, and other attributes will require geologic and geophysical studies that are somewhat analogous to studies conducted for petroleum exploration. In this case we are exploring for adequate storage space.

Storage of CO_2 in coal beds also has large uncertainties. The coal used for CO_2 storage needs to be identified as unmineable because mining after storage will release the CO_2. The criteria for identifying unmineable coal are not well defined. Second, we have relatively little information on the properties that control the maximum amount of CO_2 that coals can adsorb and store. Recent research shows that the volume of CO_2 adsorbed per unit volume of coal can vary by a factor of two among different coal types. If we include use of CO_2 for enhanced coalbed methane recovery to offset costs of sequestration, the uncertainties get larger, perhaps as much as a factor of 10. The ratio of carbon dioxide to methane adsorption on coals varies by an order of magnitude across the full range of coal rank. There is no doubt that coal can be used to store

CO_2, and it is clear that CO_2 injection can enhance coalbed methane recovery, but it is not clear what fraction of known coal occurrences could be used for storage.

V. The "Known Resource" of Storage Capacity

The "known resource" of any fossil fuel is the cumulative production plus the known reserve. The continental United States and the offshore Gulf of Mexico have been extensively explored for oil and gas with over three million wells drilled. Cumulative production of oil from these areas is about 188 BBO and gas is about 1000 TCF as of 2001. If we make a very simplistic model of sequestration of CO_2 in oil and gas reservoirs as replacement of fluid on a volume of CO_2 per volume of oil or gas, then we can calculate the storage capacity of known oil and gas traps. If we simply divide the equivalent volumes of CO_2 gas or oil for 0.5 Gt(C) into the volume of cumulative production, we can estimate that depleted gas reservoirs could provide about 28 years of storage and depleted oil reservoirs about 34 years of storage. If these numbers are combined conservatively, there is on the order of 50 years of storage capacity at a storage rate of 0.5 Gt(C) per year.

By using the term "known resource" of CO_2 storage capacity I am making an analogy to petroleum resource assessment. Petroleum reservoirs are potential storage sites that are well characterized with a known seal and trapping volume. However, because petroleum reservoirs are part of saline formations, they can be considered the "best" part of saline formations for near-term sequestration sites. The volume of saline formations outside of petroleum accumulations, and the volume of unmineable coal, can be considered the "potential resource". We know that there is more storage volume than the known resource, but we must do further characterization to move that additional volume from "potential" to "known".

VI. Critical Issues

The storage volume for emissions from individual power plants is large. The projected area at the surface of the CO_2 storage volume required for large (1000 MWe, 8 Mt/yr CO_2) power plants over a 50 year project lifetime will be large, on the order of 100 square miles with a volume larger than a one billion barrel oil field (Brennan and Burruss, 2003). The number of individual petroleum reservoirs of this size is limited. Implementation of CO_2 capture and storage at the scale of current U.S. emissions from power plants will exceed the volume of known petroleum reservoirs in the U.S. in 50 to 100 years and require storage in saline formations. This will require characterization and monitoring of large rock volumes. Three-dimensional (3-D) and time-lapse 3-D seismic methods are obvious possible approaches but additional methods and new technologies will be necessary (Benson and Myer, 2002).

The technology for CO_2 capture will impact implementation of geologic sequestration because it will affect the relative locations of sources and sinks and the infrastructure necessary to connect them. Most of the largest point sources of CO_2 are in the eastern U.S. whereas most of the largest depleted oil and gas traps are in the southern and western U.S. (Burruss, Brennan, and Glazebrook, 2003). Current or future technology for CO_2 capture that can be retrofitted to existing coal-fired power stations will require an extensive CO_2 pipeline network to move large volumes of CO_2 from source to sink. The alternative is CO_2 capture integrated into new gasification power plants for hydrogen production and electrical generation. These installations could be located at the sites for CO_2 storage with power distributed through the electrical grid and a hydrogen transportation system.

VII. Conclusions and Future Directions

The CO_2 storage capacity of known oil and gas reservoirs in the United States is adequate to accumulate emissions from large point sources with total annual emissions of about 0.5 Gt carbon for a period of 20 to 50 years. These traps have retained buoyant fluids for millions of years.

Near-term large-scale geologic sequestration projects will probably proceed as CO_2 enhanced oil recovery projects. The economic return from oil recovery will significantly offset the cost of CO_2 capture and storage. Such projects must be large enough (equal to or larger than existing projects of 0.5 to 1.0 million tons CO_2 per year) to allow evaluation of technologies for measuring, monitoring and verification that can be scaled up to the size of realistic coal-fired power stations (1000 MWe). As the technologies evolve for CO_2 capture and storage and measurement, monitoring, and verification of stored CO_2, the storage capacity of known oil and gas traps will increase (similar to reserve growth in petroleum resource assessments (Fischer, 2002)). However, at some point we will exhaust the "best" traps, especially those best for integrated sequestration and EOR. Although additional storage capacity will be available in saline formations, we must be moving forward with low-CO_2 energy technologies that will decrease the demand for CO_2 storage as worldwide demand for energy continues to grow.

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[1] This is an important distinction to make. From the perspective of groundwater hydrology, the term "reservoir" applies to the whole formation from which water can be produced. This is distinct from the common use of this term in petroleum geology to define a specific three-dimensional structure with a low-permeability seal that can retain buoyant fluids.

policy

Advanced Nuclear Power Generation

technology

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National Commission on Energy Policy

Advanced Nuclear Power Generation

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Pew Center/NCEP 10-50 Workshop

Nuclear Power and Climate Change – Overview Paper

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I. Introduction and Summary

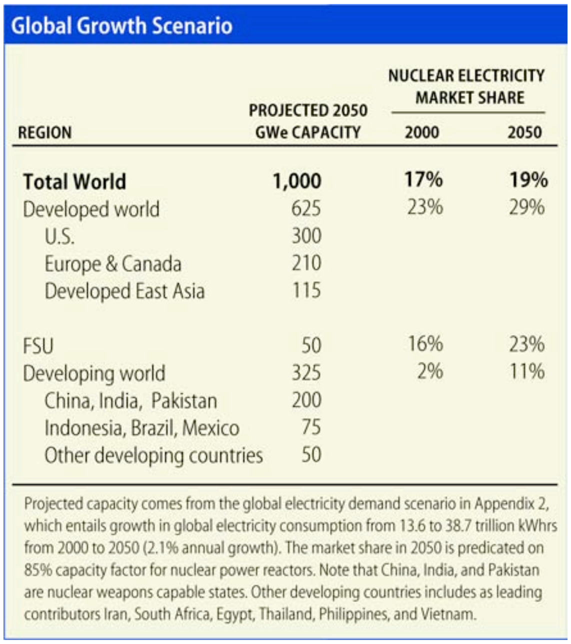
An interdisciplinary MIT study on The Future of Nuclear Power [1] was issued in Summer 2003 with a defining framework very close in spirit to that of this workshop: a mid-century scenario was established in which nuclear power could make a significant contribution to mitigating greenhouse gas (GHG) emissions, and policy options and actions for the next decade that sustain the nuclear option were described. Indeed, the rather diverse faculty study group – drawn from the Schools of Science, of Engineering, of Humanities and Social Sciences, and of Management, and from Harvard's Kennedy School of Government – came together for the study because of the shared conviction that GHG emissions must be reduced dramatically relative to the expected increase in energy use and that the United States will eventually join with others to do so. Further, a prudent target of achieving GHG emissions below today's levels at mid-century, when energy use will probably have increased two to two and a half times today's, is so daunting that all energy options – greatly increased efficiency, renewables, carbon capture and sequestration, and nuclear power – are likely to be needed. For nuclear power, economic, safety, nuclear waste, and nuclear proliferation all present challenges that must be overcome technically, operationally, and in terms of public acceptance. The report provides integrated recommendations to address these challenges. Key observations and recommendations include:

- A mid-century growth scenario on a scale that substantially impacts GHG emissions would be realized with thermal reactors operated principally in a once-through mode [2], with economic criteria being crucial in driving this technology pathway.
- A merchant plant model of costs shows that, if nuclear power is to be competitive with coal and natural gas, industry must demonstrate reactor capital cost reductions that are plausible but as yet unproved, and the social costs of GHG emissions need to be internalized. For the United States, overcoming the "first mover" problem is key to determining the role of nuclear power. We recommend electricity production tax credits for "first movers", modeled after those in place for wind. First mover demonstration of the economics and safety of new nuclear plants must occur within the next decade or so if nuclear power is to make a significant contribution to mitigating climate change in the first half of this century.

- Long-term storage of spent fuel prior to geological emplacement, specifically including international spent fuel storage, should be systematically incorporated into waste management strategies. The scope of waste management research and development (R&D) should be expanded significantly; an extensive program on deep borehole disposal is an example. Successful operation of geological disposal facilities and public acceptance of the soundness of this approach are essential for large-scale new nuclear power deployment.
- The current international safeguards regime should be strengthened to meet the nonproliferation challenges of globally expanded nuclear power. The International Atomic Energy Agency (IAEA) Additional Protocol [3] needs to be implemented, and the accounting and inspection regime should be supplemented with strong surveillance and containment systems for new fuel cycle facilities. The Nonproliferation Treaty implementation framework should evolve to a risk-based framework keyed to fuel cycle activity; central to this is having growth in global nuclear power deployment realized by having fuel cycle services, in particular fresh fuel supply and spent fuel removal, provided by a relatively small number of suppliers under international oversight. Such an approach needs to be established over the next decade, prior to a possible acceleration in nuclear power deployment.
- A major international effort should be launched to develop the analytical tools and to collect essential scientific and engineering data for integrated assessment of fuel cycles (advanced fuels, reactors, irradiated fuel reprocessing, waste management). Large demonstration projects are not justified in the absence of advanced analysis and simulation capability.
- Public acceptance is critical to expansion of nuclear power in many countries. In the United States, the public does not yet see nuclear power as a way to address global warming.

II. Global Growth Scenario

Our policy recommendations are strongly influenced both by the mid-century time scale for meaningful response to global climate change and by the concomitant scale and spread of the needed technology deployment. To help guide the analysis, we constructed a scenario for global growth of electricity demand and for nuclear power's share of that growth. The scenario for electricity demand was based on U.N. world population and urbanization projections and an assumption of national per capita electricity consumption rising towards a world standard. The resulting projection for global electricity production is consistent with U.S. Energy Information Administration (EIA) projections over the next two decades (slightly below the EIA reference case) and yields an increase of nearly a factor of three by mid-century. The nuclear power market share, assuming a strong impetus to deploy nuclear power (presumably because of GHG emission "caps" and of satisfactory resolution of the challenges noted above), is based upon national capabilities and infrastructure. The resulting scenario is shown in Table 1.



Global Growth Scenario

REGION	PROJECTED 2050 GWe CAPACITY	NUCLEAR ELECTRICITY MARKET SHARE 2000	NUCLEAR ELECTRICITY MARKET SHARE 2050
Total World	**1,000**	**17%**	**19%**
Developed world	625	23%	29%
U.S.	300		
Europe & Canada	210		
Developed East Asia	115		
FSU	50	16%	23%
Developing world	325	2%	11%
China, India, Pakistan	200		
Indonesia, Brazil, Mexico	75		
Other developing countries	50		

Projected capacity comes from the global electricity demand scenario in Appendix 2, which entails growth in global electricity consumption from 13.6 to 38.7 trillion kWhrs from 2000 to 2050 (2.1% annual growth). The market share in 2050 is predicated on 85% capacity factor for nuclear power reactors. Note that China, India, and Pakistan are nuclear weapons capable states. Other developing countries includes as leading contributors Iran, South Africa, Egypt, Thailand, Philippines, and Vietnam.

Table 1

Several features of the scenario deserve note. The total deployment of 1000 Gigawatts electric (GWe) globally is nearly a tripling of today's deployment. This corresponds to an approximately level world market share and would displace about 1.8 Gigatonnes of carbon (equivalent) emissions annually from coal plants of equivalent capacity [4]. Such a displacement might represent about 25% of incremental GHG emissions from energy use in a business-as-usual scenario, a significant amount. Indeed, one may question whether difficult public policy steps are worthwhile from a climate change perspective unless one envisions nuclear power contributing to the "solution" at this level.

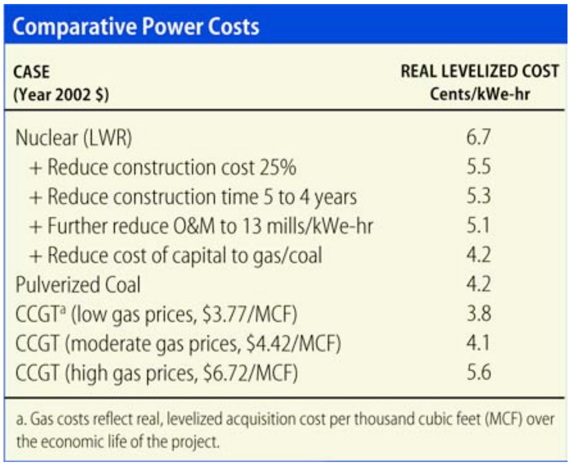
To reach such a level, the developed world will need to increase its nuclear market share substantially, up to about 30%. In particular, the United States must play a lead role, because of the combination of high per capita demand and projected population increase of about 100 million people. The reality that no new nuclear plants have been ordered in the United States for a quarter century is one indicator of the difficulty in realizing this global scenario. In contrast to the U.S. situation, projected stable (e.g., France) or declining (e.g., Japan) populations in countries seen today as more favorably disposed to nuclear power serve to limit demand growth.

A substantial part of the growth also occurs in the developing economies, but in a relatively small number of countries. This has important implications for addressing proliferation concerns, particularly since China, India and Pakistan already have nuclear weapons capabilities and thus are not major concerns for fuel cycle-associated proliferation (since they are likely to continue with dedicated weapons programs).

III. Economics

The economic comparison of new nuclear plants with baseload coal and natural gas plants and the economics of closing the fuel cycle underpin many of the recommendations. The baseline costs for new plants were compared within a framework of:

- merchant plants (i.e., a competitive generation market in which investors bear the primary risk)
- experience, rather than engineering analyses
- lifetime levelized costs.



Comparative Power Costs

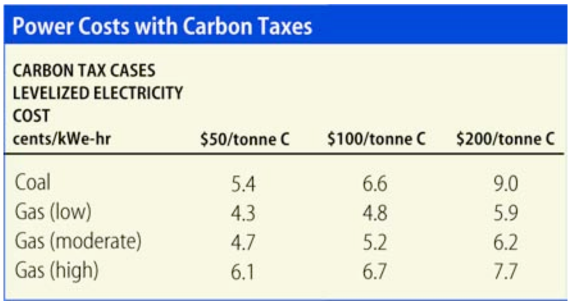
CASE (Year 2002 $)	REAL LEVELIZED COST Cents/kWe-hr
Nuclear (LWR)	6.7
+ Reduce construction cost 25%	5.5
+ Reduce construction time 5 to 4 years	5.3
+ Further reduce O&M to 13 mills/kWe-hr	5.1
+ Reduce cost of capital to gas/coal	4.2
Pulverized Coal	4.2
CCGT[a] (low gas prices, $3.77/MCF)	3.8
CCGT (moderate gas prices, $4.42/MCF)	4.1
CCGT (high gas prices, $6.72/MCF)	5.6

a. Gas costs reflect real, levelized acquisition cost per thousand cubic feet (MCF) over the economic life of the project.

Table 2

Table 2 shows that, with gas prices of about $4.50/MCF (typical of the last year), both pulverized coal and natural gas combined cycle plants have a substantial cost advantage relative to the nuclear plant baseline in the absence of a carbon "tax" (detailed discussions of the methodology and of the input parameters can be found in the MIT report). An independent analysis performed by Deutsche Bank [5] is in quite close agreement. This comparison may be altered significantly by two factors.

- First, as shown in Table 2, plausible reductions in new nuclear plant costs can bring them in line with coal and gas. Reducing capital costs by 25% to $1500/kWe, a target that has not yet been met but appears plausible with new systems approaches and enough experience, has a large financial impact. A similar impact would arise from eliminating the risk premium (higher equity requirements and higher return on equity) for financing nuclear plants. Presumably, this reduction in the cost of financing would be achieved only by building and operating several plants successfully.
- The second major factor is the uncertainty surrounding internalization of carbon emission costs. Table 3 shows the impact of a carbon "tax" on the levelized costs for coal and gas. Clearly, the competitiveness of nuclear power would be enhanced significantly if carbon emission costs are internalized at $50 to $100 per tonne, which is considerably less than the cost of carbon dioxide capture and sequestration using today's technologies for either pulverized coal or natural gas [6].



Power Costs with Carbon Taxes

CARBON TAX CASES LEVELIZED ELECTRICITY COST cents/kWe-hr	$50/tonne C	$100/tonne C	$200/tonne C
Coal	5.4	6.6	9.0
Gas (low)	4.3	4.8	5.9
Gas (moderate)	4.7	5.2	6.2
Gas (high)	6.1	6.7	7.7

Table 3

If nuclear power is to be deployed at mid-century on the scale being discussed, substantial construction of new plants must be underway within ten to fifteen years. Both the economics and new regulatory procedures need to be demonstrated. We recommend, for the United States, that production tax credits be offered to first mover nuclear plants at a rate set by that for wind. This is currently 1.8 cents/kWh, which can be thought of as about $75/tonne [4] of avoided carbon from a coal plant (and with the public benefit of carbon avoidance for decades following expiration of the credit). A production tax credit has the advantages of fundamentally keeping the risk with the private sector and of being applicable to any carbon-free option. Because of the very different natures of nuclear power and wind with respect to baseload characteristics, we recommended limiting the credit to 10 GWe of first mover capacity and to a total of about $200/kW. This recommendation is reflected in the 2003 energy bill conference report, although with less eligible capacity and a potentially much higher credit per installed kilowatt. The public good argument for such a mechanism rests with the importance of having government, industry, and financial markets understand whether new nuclear power will be competitive with fossil fuels and thus a serious option for meeting electricity demand and addressing climate change.

The utility view, as represented in the workshop submission [7] of Marilyn Kray (Exelon), for moving to new nuclear construction supports this approach. Three principal criteria are offered:

- operational confidence based on familiarity with the system designs and standardization of both design and operation;
- licenseability, for which the extensive regulatory history with light water reactors is very important; and
- economics, requiring large reductions in overnight capital costs compared to past experience.

The “first mover” reactors are overwhelmingly likely to be evolutionary advances of operating reactors, with passive safety features replacing some of the active systems in today’s plants. This addresses the first two criteria, while the tax credit provides the incentive to determine the economics. Clearly other criteria will also need to be met to make a business decision; Kray [7] mentions: reliable demand for baseload electricity; cost of alternatives, especially natural gas prices; continued successful operations of existing nuclear plants and a path to resolve plant security and spent fuel disposal issues; regulatory predictability through the Combined Operating License process; possible risk sharing through a “first mover consortium;” and recognition of the environmental benefits.

Tom Cochran (NRDC), in another workshop submission [8], argues against the first mover production tax credit as a subsidy that will not reduce the real cost of U.S. nuclear power plants. The MIT study group agrees that the tax credit will not itself reduce costs; rather, it is an incentive to take the first mover risk. If the industry is not confident in meeting cost targets with a substantial production tax credit available for several plants (allowing cost reduction through experience and by spreading one-time costs), then the credit will go unused with the obvious implications for nuclear power's role in meeting GHG challenges.

The MIT study also looks at the economics of plutonium recycling in the PUREX/MOX [9] fuel cycle. Not surprisingly, the once-through fuel cycle costs less. This is reflected indirectly in the difficulty of funding military plutonium disposition programs, where MOX fabrication costs alone are seen to equal the entire once-through fuel costs, and in the indefensible accumulation of about 200 tonnes of separated plutonium from power reactors. The arguments given in the past for pursuing PUREX/MOX have been inadequacy of uranium resources, which is no longer a credible argument, and the energy value in the plutonium, which is basically answered by the unfavorable economics. The current reason offered is the benefit to long-term waste management, to which we now turn.

IV. Nuclear Waste Management

The management and disposition of irradiated nuclear fuel has not yet been dealt with anywhere in the world. This is a major impediment to the growth of nuclear power. The Yucca Mountain repository is moving towards a licensing decision and, if it proceeds to successful implementation, a major milestone will have been achieved. Nevertheless, the MIT study's growth scenario calls for a dramatically expanded capacity for waste management in any fuel cycle.

Partitioning of the spent fuel to remove plutonium and possibly other actinides unquestionably reduces long-term radioactivity and toxicity of the waste. Nevertheless, the MIT study group did not find the benefits of partitioning and transmutation to be compelling on the basis of waste management. There are several reasons. First, although successful implementation has not yet been demonstrated, the scientific basis for long-term geological isolation appears sound. Partitioning leads to a large volume and mass reduction, but these are not terribly important criteria for repository design. Heat and radioactivity, which are far more important criteria, are only marginally reduced on the century time scale, since the fission products remain with the waste. In addition, the trade-off of benefits – possibly of small consequence to human health - in the millennium time scale against near-term increases in waste streams, occupational exposure, and safety concerns is not clear. There is certainly little evidence that the public is more concerned with the millennium rather than the generational time scale. Finally, other approaches may yield even greater confidence in long-term isolation and may do so more economically and simply. This would include advanced engineered barriers and other disposal approaches, such as deep boreholes. These are modest diameter holes drilled 4 to 5 kilometers deep into stable crystalline rock. The approach looks promising and economical because of drilling advances, because the geochemical environment (highly reducing) is favorable, and because the emplacement is not subject to surface vagaries. This is not to say that deep boreholes will prove to be the best approach, since major uncertainties exist. The point is that important alternatives to partitioning exist for adding even greater confidence to long-term waste isolation and these should be explored vigorously through new R&D programs.

An important role for advanced fuel cycles well into the future cannot be excluded, although significant economic and technical barriers must be overcome. The MIT study recommends a program of analysis, simulation tool development, and basic science and engineering of advanced concepts, and eventually appropriate project demonstrations. Cochran [8] argues that such a program is in itself a proliferation risk. We concur that such a program carries risk. However, the U.S. approach of rejecting plutonium recycle and cutting off research and international cooperation on fuel cycles demonstrably proved ineffective, since other countries have moved forward anyway. Rejection of the civilian MOX option should continue. Our recommendation is one of U.S. engagement to shape international advanced fuel cycle R&D properly, with an open mind to its eventual outcome, even while pursuing and advocating the open fuel cycle with thermal reactors as the basis for growth over the next decades. We also recommend that the U.S. government offices responsible for nonproliferation have an explicit management role in defining the scope, scale and location of such international R&D programs.

V. Nonproliferation

Global expansion of nuclear power into numerous new countries raises concerns about proliferation. This is not new, since a similar concern formed the backdrop for President Eisenhower's "Atoms for Peace" speech fifty years ago. However, the nonproliferation regime rooted in the Nuclear Nonproliferation Treaty (NPT) framework faces new circumstances: the end of the Cold War has changed security threats and relationships; the dramatic spread of manufacturing capability and technology lowers the barriers for translating nuclear know-how into nuclear weapons; and the post-9/11 world is more aware of the capabilities of terrorist groups and their interest in nuclear materials. These realities have refocused attention on the control and elimination of weapons-usable fissionable material (HEU and plutonium) and on the uncomfortable recognition that countries can move to the threshold of a nuclear weapons capability within the NPT regime.

Strengthening the nonproliferation regime in the face of a possible global nuclear power growth scenario calls for many coordinated actions. One fundamental change to the NPT implementation regime, discussed in the MIT report, would focus on a risk-based framework rooted in the technology, as opposed to political views. The key issue is that power reactors are not themselves the major proliferation threat, as opposed to enrichment and reprocessing plants, in the fuel cycle. Thus, states that deploy only reactors, with international assistance as desired, would have internationally secured fresh fuel supply and spent fuel removal. This would involve either "fuel cycle states" or internationally operated fuel cycle centers. The advantages of a country taking a "reactor-only" path would be avoidance of significant nuclear fuel cycle infrastructure development and maintenance costs, of intrusive safeguards regimes (since spent fuel and refueling operations for light water reactors are relatively easily monitored), and, most important, of nuclear waste challenges. An insistence on developing a full fuel cycle infrastructure, given the option of internationally guaranteed, economically attractive fuel cycle services and avoidance of significant challenges (especially waste management), would greatly heighten suspicions about proliferation intent, presumably leading to toughened international control mechanisms with regard to such countries. The major obstacle is acceptance of the spent fuel in a multiplicity of countries. So far, only Russia has expressed interest in receiving such fuel. This willingness of Russia to accept return of spent fuel may yet facilitate a resolution of the concerns about Iran's nuclear infrastructure development, a resolution much along the lines being suggested here for broader application. Clearly, establishing the validity of long-term secure spent fuel and/or high-level waste geological isolation is a critical step for responsible growth of nuclear power in response to electricity supply and climate change imperatives.

VI. Public Attitudes

The MIT study carried out a poll of well over 1000 Americans on their attitudes and understanding of energy-related issues. By and large, the public has a good understanding of relative costs and environmental impacts of different technologies; the cost of renewables was a notable exception, in that these were widely thought to be inexpensive. Nevertheless, it was interesting that perceptions of technology, rather than "external" factors such as politics or demographics, were at the core of their attitudes. A majority of respondents did not believe that nuclear waste can be stored safely for many years, and the typical respondent believed that a serious reactor accident is somewhat likely in the next ten years. The poll also showed that, in the United States, the public does not connect concern about global warming with carbon-"free" nuclear power. There is no difference in support for building more nuclear power plants between those who are very concerned about global warming and those who are not. This may prove to be either an opportunity for nuclear power advocates to better educate the public or a major obstacle to motivating the growth scenario.

VII. Concluding Remarks

The MIT study sought to define actions needed to enable nuclear power as an option for significantly mitigating GHG emissions while satisfying increasing global demand for electricity. If expansion of nuclear power is to contribute in a meaningful way up to mid-century, a robust growth period must commence within ten to fifteen years. This in turn means that very soon costs of new plants must be understood, including those costs driven by the licensing process and possible litigation, and issues surrounding waste management must be resolved. Recommendations for addressing the risks associated with first mover plants, in particular first mover production tax credits, were put forward and may be implemented. This is a necessary but not sufficient condition for the robust growth scenario. In addition, difficult international nonproliferation measures must be adopted and nuclear spent fuel management programs must demonstrate successful implementation and earn widespread public acceptance. These challenges are linked in ways that are complicated by the very different nuclear policies of the United States and some of its allies. Only if these challenges are met can nuclear power responsibly expand to the terawatt scale needed for seriously contributing to climate change mitigation at mid-century.

References and Notes

[1] *The Future of Nuclear Power*, ISBN 0-615-12420-8 (July 2003), available on-line at http://web.mit.edu/nuclearpower/; this workshop paper is largely drawn from this report. The study was funded principally by the Sloan Foundation. Study group members were Professors S. Ansolabehere, J. Deutch (co-chair), M. Driscoll, P. Gray, J. Holdren, P. Joskow, R. Lester, E. Moniz (co-chair), and N. Todreas.

[2] A nuclear reactor produces energy through fission, or splitting, of certain uranium or plutonium isotopes when struck by a neutron. The fission process itself produces neutrons, leading to the possibility of a chain reaction. A thermal reactor is one in which the produced neutrons are slowed down in order to increase greatly the probability of succeeding fissions. The light water reactors prevalent today are of this type. The once-through mode means removing the spent fuel for geological disposal. Closed fuel cycles are those in which the irradiated fuel is chemically processed to separate and recycle in the reactor components that have energy value, principally plutonium.

[3] The Additional Protocol permits the IAEA to inspect undeclared facilities suspected of use in a nuclear weapons development program.

[4] For the reference coal plant, we take a capacity factor of 85%, a heat rate of 9,300 Btu, and a carbon intensity of 25.8 kg-C/mmBtu.

[5] Adam Siemenski, Deutsche Bank, presentation at the 2002 EIA NEMS conference.

[6] David, J. and H. Herzog, "The Cost of Carbon Capture," Fifth International Conference on Greenhouse Gas Control Technologies (Australia, 2000); available at http://sequestration.mit.edu.

[7] Kray, Marilyn C. 2004. Long-Term Strategy for Nuclear Power. Paper prepared for the Pew/NCEP "10-50 Solution" Workshop. Washington, D.C., March 25–26, 2004.

[8] Cochran, Thomas B., Critique of "The Future of Nuclear Power: An Interdisciplinary MIT Study." Paper prepared for the Pew/NCEP "10-50 Solution" Workshop. Washington, D.C., March 25–26, 2004.

[9] The PUREX/MOX fuel cycle is the closed fuel cycle in operation today in France and a few other countries. PUREX is a specific chemical process for separating plutonium and uranium from fission products (and minor actinides). MOX is the mixed plutonium oxide and uranium oxide fuel fabricated from the recycled plutonium.

Pew Center/NCEP 10-50 Workshop

Critique of "The Future of Nuclear Power: An Interdisciplinary MIT Study"

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Natural Resources Defense Council

"The Future of Nuclear Power: An Interdisciplinary MIT Study" (hereafter, the "MIT Study") is the work of nine professors, eight from MIT and one from Harvard. The two principal investigators were former senior officials at the Department of Energy (DOE) managing the department's nuclear energy research and development (R&D) programs, and three other study group members were from MIT's Department of Nuclear Engineering. Most if not all of the study participants were predisposed to support the retention of nuclear power in some capacity. Nuclear power's usefulness as an option for reducing GHG emissions was the rationale for the study and was developed as its central theme.

The MIT Study includes an excellent analysis of the current economic plight of the U.S. nuclear industry. It makes clear that new nuclear plants are not economical and a combination of factors will have to break in nuclear's favor for new nuclear generators to be economically competitive with gas and coal. In the words of the study:

> In deregulated markets, nuclear power is not now competitive with coal and natural gas. However, plausible reductions by industry in capital cost, operation and maintenance costs, and construction time could reduce the gap. Carbon emission credits, if enacted by government, can give nuclear power an advantage. (MIT Study, p. ix)

Favoring nuclear power but recognizing that new nuclear plants are not competitive, the study group recommends that the U.S. government subsidize the technology to "resolve uncertainties about the economics of nuclear power" (MIT Study, p. 77). The recommended subsidies include the government sharing in the cost of obtaining Nuclear Regulatory Commission (NRC) approval for new plant sites, in the fees for NRC certification of new designs and in the fees for NRC construction and operating licenses, and "a production tax credit for up to $200/kWe [i.e., $200 per kilowatt of electric power] of the plants construction tax credit" for ten so-called "first mover" plants (MIT Study, pp. 80-81). This last proposed subsidy is pegged to the 1.7 cent per kilowatt–hour production tax credit for wind energy, and alone represents an additional $2 billion worth of subsidies for nuclear power plants to be constructed in the United States (MIT Study, p. 81). The study group also endorsed DOE's 2010 initiative, under which DOE is subsidizing—to the tune of hundreds of millions of dollars—certification of new reactor designs and early site banking of new nuclear plant sites.

These proposed subsidies are unjustified in my view, promoting both negative economic and environmental consequences relative to more benign renewable energy generating technologies. Moreover, nuclear power is a mature industry that has already benefited from tens of billions of dollars in government subsidies over many decades and should sink or swim of its own accord without additional taxpayer assistance.

The reactor design certification primarily benefits foreign reactor manufactures since three of five former U.S. reactor vendors are now owned by foreign companies. Moreover, certification by the NRC of new reactor designs is sought by the vendors primarily to aid in selling these designs in foreign markets rather than in the United States. It functions as a "stamp of approval" suggesting that the designs are safe for export.

Under the MIT Study proposal large profitable U.S. nuclear generation companies would receive hundreds of millions of dollars in government subsidies through cost-sharing arrangements to bank sites[1] without being asked to make an upfront commitment to build a new nuclear plant should the sites be approved by the NRC. Moreover, early banking of reactor sites has the detrimental effect of reducing the likelihood that affected citizens can effectively participate in the licensing process.

Most importantly, giving a few large U.S. nuclear energy generating companies $2-3 billion dollars of taxpayer monies is not going to make new nuclear plants economical. It may lead to the subsidized construction of a few new plants, but it does nothing to reduce the real cost of nuclear power plants built in the United States. The study group argues that it will reduce the investor uncertainty in new plant costs. By this logic, the government should subsidize new energy conservation technologies and new pollution control equipment for fossil-fueled power plants.

The study group pegged its recommended production tax credit subsidy to that given to wind power. But the environmental costs of the two technologies are markedly different. While neither wind nor nuclear power contributes significantly to GHG emissions, nuclear power carries considerable baggage that sets it apart from wind power. Nuclear power has unresolved proliferation, safety and waste disposal problems that are unique to the technology. The MIT Study notes key unresolved issues in each of these areas, but instead of calling for their resolution, the pro-nuclear industry study group calls for multi-billion dollar government nuclear subsidies to build new nuclear plants.

Since most *existing* nuclear plants are economically competitive with fossil-fueled plants in terms of forward costs, energy generating companies will continue to extend the licenses and operate the existing U.S. fleet of nuclear plants over the next several decades. Also, since subsidizing a few new plants is not going to make *new* nuclear plants competitive, there are unlikely to be significant additions to the fleet beyond possibly a few heavily subsidized plants. Consequently, over the next fifty years I believe the number of nuclear plants in the United States will be on the order of 80 to 110 plants, where the low end of the range is based on the assumption that some older plants may be shut down and essentially no new plants will be constructed, and the upper end of the range assumes that few of the existing plants will be shut down and the government will subsidized the construction of several new plants.

The MIT Study also recommends that,

> Federal or State portfolio standards should include incremental nuclear power capacity as a carbon free source. (MIT Study, p. x)

I do not support this recommendation because, as noted above, there are serious unresolved safety, nonproliferation and high-level waste disposal problems that are uniquely associated with nuclear power.

Another major disagreement I have with the study group's recommendations is related to fuel cycle research. As before, while the analysis of the problem is correct, the recommendations fall short. The MIT Study correctly notes:

> **. . . over the next 50 years the best choice . . . is the open, once-through fuel cycle.** (MIT Study, p. x, emphasis in the text)

and

> *For the next decades, governments and industry in the U.S. and elsewhere should give priority to the development of the once-through fuel cycle, rather than the development of more expensive closed fuel cycle technology involving reprocessing and new advanced thermal or fast reactor technologies.*
> This recommendation implies a major re-ordering of priorities of the U.S. Department of Energy nuclear R&D programs. (MIT Study, p. 5, emphasis in the text)

and

> *We believe that the world-wide supply of uranium ore is sufficient to fuel the development of 1000 reactors over the next half century* and to maintain this level of development over a 40 year lifetime of this fleet. (MIT Study, p. 4, emphasis in the text)

Support for these conclusions can be found in Appendix 5.E at page 154 of the MIT Study where there is a figure that shows that during the 20th century, the constant dollar price of 12 selected minerals went down. This downward trend reflects the fact the efficiencies in extraction ores outpaced the depletion of the higher grades. This trend, which goes unrecognized by most nuclear engineers, is true of virtually all major mineral resources. The fact that it is also true of uranium could be seen more clearly had Figure A-5.E.1 (MIT Study, p. 153) been plotted in constant dollars instead of current dollars.

The MIT Study also recognizes that closed fuel cycles are grossly uneconomical compared to the open cycle.

> The fuel cycle cost model presented in Appendix 5.D shows that the closed cycle PUREX/MOX option fuel costs are roughly 4 times greater than for the open cycle, using estimated costs under U.S. conditions. (MIT Study, p. 44)

In Appendix 5.D the PUREX/MOX option cost was estimated to be $8890/kgHM compared to $2040/kgHM for the open cycle. The open cycle costs in the U.S. are well known based on decades of experience. The closed cycle costs are likely to be considerably higher than those estimated by the MIT Study, which pegs the reprocessing cost at only $1000/kgHM. Based on European and Japanese experience, this cost is likely to be one or two times higher. The cost estimate of MOX fabrication also appears to be low. Moreover, the advanced closed fuel cycles are likely to be even more economically disadvantageous, as can be deduced from the pilot pyro-processing experience in the United States.

The MIT Study also concludes,

> *. . . we do not believe a convincing case can be made on the basis of waste management considerations alone that the benefits of advanced fuel cycle schemes featuring waste partitioning and transmutation will outweigh the attendant risks and costs.* (MIT Study, p. 60, emphasis in the text)

In addition, the MIT Study recognizes that the closed fuel cycle represents a serious proliferation threat when undertaken in any number of non-weapon states, e.g., Iraq, Iran, North Korea, and even Russia.

Despite the acknowledgement of poor economic prospects, no significant waste management advantages and high proliferation risks associated with closed fuel cycles, the MIT Study unfortunately leaves the door open to develop new reprocessing technologies.

> On the other hand, we [the MIT Study group] support modest laboratory scale research and analysis on new separation methods with the objective to learn about separation methods that are less costly and more proliferation resistant. There has been little exploration in the United States of alternatives to PUREX and pyro-processing since their invention decades ago with entirely different purposes in mind: obtaining weapons usable material and reprocessing metal fuel, respectively. We note however that there is considerable skepticism for even this modest approach, because some see *any* U.S. work on reprocessing sending the wrong signal to other nations about the credibility of our expressed attitude toward the proliferation risks of reprocessing, and the concern that DOE will move from analysis and research to development before the technical basis for such action has been developed. We propose that this program begin at a modest scale, reaching $10 million per year in about five years. (MIT Study, p. 92)

Instead of curbing DOE's appetite for promoting technologies that are both dangerous and uneconomical, this MIT Study recommendation likely will be used by DOE to justify its Advanced Fuel Cycle Initiative (AFCI). The DOE FY 2004 budget for the AFCI is $63 million—over six times what the MIT recommends be spent in five years. The AFCI is coordinated with DOE's Generation IV program to develop new reactor concepts for possible introduction in the 2030 to 2050 time period. Last year DOE organized the Generation-IV International Forum, an effort by 10 countries to jointly develop six nuclear energy systems, including several fast reactor concepts that require closed fuel cycles. The countries included five non-weapon states that formerly had clandestine nuclear weapon programs, namely, South Africa, Argentina, Brazil, South Korea and Switzerland.

Although the MIT Study recommends that "[t]he DOE R&D program should be realigned to focus on the open, once-through fuel cycle" (MIT Study, p. x), I fear the recommendation to engage in modest R&D on closed fuel cycles will be used to bolster the DOE AFCI effort. This will promote in non-weapon states, including states that in the past had clandestine nuclear weapon programs, the construction of hot cells for reprocessing R&D and training of cadres of experts in plutonium chemistry and metallurgy. This DOE effort is clearly a threat to U.S. national security.

Because closed fuel cycles are so uneconomical, U.S. government sponsored research on closed fuel cycles is not likely to lead to their adoption. Consequently, in the next fifty years I believe U.S. nuclear plants will stick with the open fuel cycle.

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[1] "Site banking" refers to the process of obtaining regulatory approval of a nuclear plant site before construction. See Deutch, John, Ernest J. Moniz, et al. 2003. *The Future of Nuclear Power—An Interdisciplinary MIT Report.* Massachusetts Institute of Technology. See http://web.mit.edu/nuclearpower/, pg. 96.

Pew Center/NCEP 10-50 Workshop

“Long-Term Strategy for Nuclear Power”

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I. Introduction

As the largest U.S. nuclear operator, Exelon Corporation is dedicated to the safety performance of its existing 17 reactors. It is committed to continuous improvement and operational excellence. As one of the largest power producers and wholesale marketers, Exelon is also focused on maintaining the long-term balance between electricity supply and demand. This paper is intended to offer insights regarding nuclear power, within the context of the long-term electricity projections.

The most notable and unrecognized attribute of nuclear power is its environmental benefit. Along with various forms of renewable energy, nuclear power is a carbon-free form of electricity generation. Nuclear power is not based on combustion, so the plants do not produce nitrogen oxides or sulfur dioxide that could contribute to ground-level ozone formation, smog or acid rain. Additionally, nuclear energy does not produce carbon dioxide or other greenhouse gases associated with global warming. The electricity produced by nuclear power plants displaces electricity that would otherwise be supplied predominantly by coal, gas or oil fired generating plants.

Most electricity forecasts predict an increase in the demand for electricity in the coming years. Nuclear power has typically provided approximately 20% of the U.S. electricity supply, despite the steady increase in electricity demand. This gradual increase in nuclear generation has been the result of the nuclear industry’s strategy to improve capacity factors[1] and increase rated output[2] of the current fleet of U.S. plants. With these generation expansions already extracted, the current fleet cannot be expected to uphold its current contribution percentage given continuous growth in demand.

Given the environmental attributes of nuclear power and the anticipated demand for electricity, nuclear power needs to remain part of the country’s overall generation strategy. Part of this strategy should include the construction of new nuclear generation to preserve the non-carbon emitting portion of total electricity generation. Although Exelon has no immediate plans for building new nuclear capacity, it is taking action to preserve and promote the nuclear option for the future.

II. Reactor Technology

One of the critical factors for the future viability of nuclear power is the readiness of advanced reactor technology. Over the span of the next 50 years, there is an emerging evolution of reactor designs. This evolution starts with the advanced light water reactors (ALWRs) that leverage the operating fundamentals of existing plants in the U.S., and replace many of the active safety components with passive features that rely on laws of nature such as gravity feed, convective heat transfer and natural circulation. The ALWR category includes designs such as the Westinghouse Advanced Passive (AP) 1000, the General Electric Advanced Boiling Water Reactor (ABWR) and the Economic Simplified Boiling Water Reactor (ESBWR). Beyond the ALWRs are the gas-cooled reactors that replace water with helium as the reactor core-cooling medium. The gas-cooled reactors appear to precede what are typically referred to as the Generation IV reactors. Although the lines of distinction regarding the Generation IV reactors are sometimes blurred, the Generation IV International Forum (GIF) has identified six reactors as meeting the specified technology goals. When considering designs for potential investment, the following three factors are considered: operational confidence, licenseability and economics.

Operational Confidence

Any investment in new nuclear technology will need to be accompanied by a high degree of operational confidence. That is, the investment analysis must not only appeal to the financial and risk evaluators, but must also be endorsed by the organization that takes ultimate responsibility in operating the facility. Operational confidence is based largely on familiarity with system designs, including the individual components and their materials, and the basic engineering philosophy governing the design. The more a design departs from proven and familiar technology, the less is its readiness for deployment. Accordingly, some of the more aggressive designs within the family of Generation IV plants are expected to require significant efforts to demonstrate the acceptability of the fuel and materials, as well as a possible prototype or demonstration plant operation before they are commercially deployed. On the other hand, the ALWR category of reactors is considered deployable following approval by the Nuclear Regulatory Commission (NRC).

One of the lessons learned from the existing U.S. fleet is the value of standardization of both design and operating practices. Although a limited number of fundamental designs were constructed, there have been numerous design changes resulting from regulatory requests and owner enhancements. For the next generation of reactors, increased discipline to prevent departure from the standard design would optimize the cost reductions resulting from economies of scale and the performance improvements resulting from the transferability of operating experience and resources. The Exelon Nuclear organization has benefited greatly from its commitment to standardize the operating practices of its 17 units under the umbrella of a common Management Model. The new generation of nuclear operators will need to adopt a similar commitment to operate the next generation of reactors safely and efficiently. The simplified reactor designs are more likely to remain standardized because there are fewer and less complicated systems and equipment for an individual owner to re-engineer.

Licenseability

Just as the future operators must be comfortable with the selected design, the regulatory reviewers of the design must be adequately satisfied. Since a few of the ALWR designs are evolutions of the currently NRC-approved reactors, it is expected that their review process would be shorter than that of other designs. Within the ALWR category is the Atomic Energy of Canada, Limited (AECL) design for the Advanced Candu Reactor (ACR) 700. The ACR 700 uses a light water coolant, but a heavy water moderator. It also employs a horizontal fuel channel designed for on-line refueling. Although these design features may prove to be acceptable to the NRC, they introduce new accident and transient scenarios that will require additional staff analysis to determine their acceptability. This is also similar for some of the gas-cooled designs that employ alternate containment designs based on fuel protection characteristics. Both the gas reactors and most of the Generation IV designs, such as the lead-cooled fast reactor or the molten salt reactor, would require even further NRC staff evaluations first to modify the existing light water-based regulations to make them applicable for the specific designs, and then to evaluate the proposed designs against the new criteria. This insight was gained through Exelon's previous interaction with the NRC staff during pre-application discussions regarding the Pebble Bed Modular Reactor (PBMR). These discussions have ended because Exelon decided to no longer pursue investment in the PBMR as a strategic initiative. The duration and extent of the licensing process are relevant in estimating the time and cost associated with the NRC licensing of the design for inclusion in the overall economic analysis.

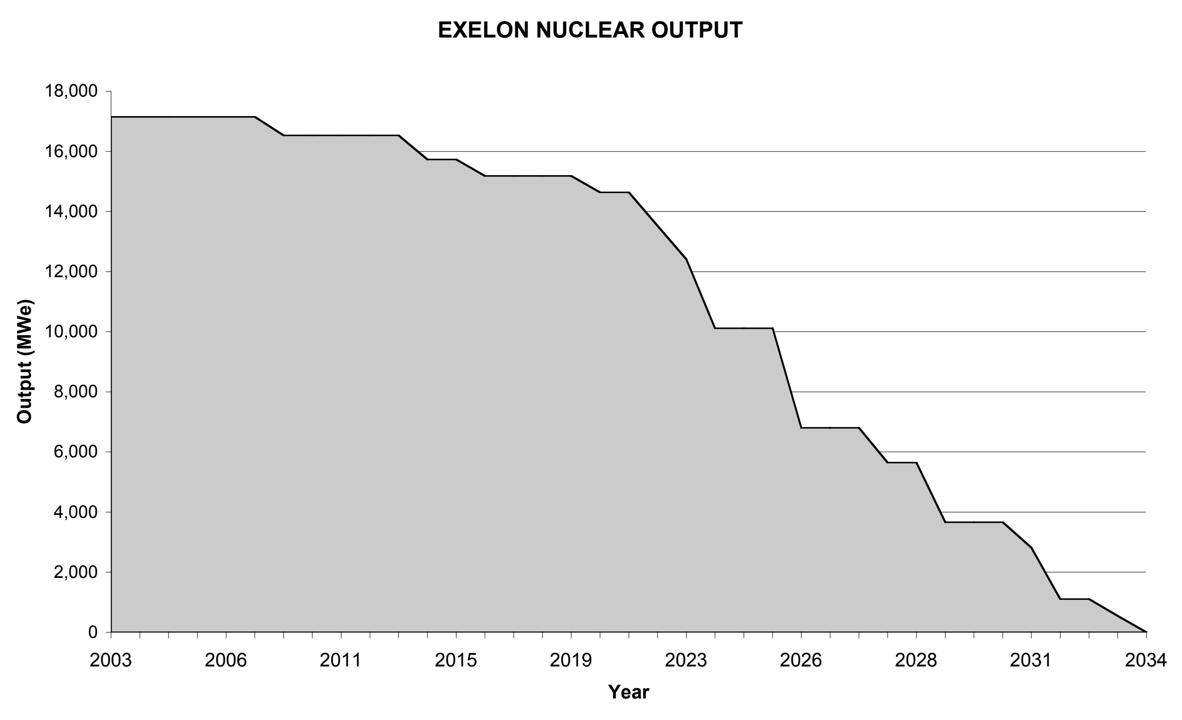
Economics

The industry has informally conveyed an acceptance window of $1000-1200/kwe for the capital cost, excluding financing, for any new nuclear facility. While the reactor vendors have acknowledged this, additional work is needed to confirm that it is achievable. In addition to the construction costs and schedule, confidence is needed in estimating the ongoing operations and maintenance costs, including fuel and staffing levels for the proposed facility. The General Electric ABWR is already operating in other countries. This significantly reduces the uncertainty around many of the economic assumptions. For plants such as the AP1000, which is not yet built, Westinghouse established a Business Plan Team comprised of several power companies, including Exelon, and an architect engineer. The team's goal was to use operational and construction experience to validate the economic data needed to support a detailed business model. It is premature at this time to make construction or operations cost estimates for the Generation IV reactor designs given the state of their design status.

III. Strategic Planning

Licensing timeframes have played a significant role in strategic planning for nuclear power. Nuclear plants have historically been licensed for a 40-year period. This original 40-year term was based on economic and antitrust considerations at the time, and not on limitations of materials or nuclear technology. As such, a licensee can voluntarily request to extend an operating license by demonstrating to the NRC that the plant continues to maintain adequate levels of safety, and this level has been enhanced through maintenance of the licensing basis over the plant's life. Approximately 10 percent of U.S. nuclear plant licenses will expire by the end of the year 2010, and more than 40 percent will expire by 2015.

As stated previously, Exelon currently operates 17 nuclear units, including three units owned through AmerGen. The chart below depicts the approximate gross electrical output of Exelon's nuclear fleet over time, including the curtailment due to license expiration. It includes Exelon's recent success in receiving NRC approval to extend the license for two units, and assumes that the application pending for an additional four units will also be successful. For the remaining units, the chart reflects each unit's current license expiration date, recognizing that license extension decisions for these units will be based on individual cost comparison analyses.



The graph above acknowledges that eventually the current fleet of reactors will retire, although retirements may be delayed by the extension of additional units. It is premature to estimate the amount and type of replacement generation needed. What is evident, however, is that having multiple options available is preferred in order to ensure price competitiveness and fuel diversity. It is hoped that breakthroughs in clean coal technology and renewable energies will be realized in the future. However, it appears realistic to assume that the void created by the nuclear retirements may require some additional nuclear power as the replacement source.

IV. Conditions for New Nuclear Investments

Any nuclear investment made by power companies must be based on a rigorous financial and risk evaluation. Many of the assumptions needed to evaluate a potential nuclear investment have a great degree of uncertainty at this time. In addition to having a passively safe reactor design available, a number of other conditions need to be met in order to enable sound investment decisions for new nuclear plants. The more significant ones are discussed briefly below.

Demand for Power

Many power companies, including Exelon, are operating in a deregulated environment. While there is no longer a need to justify an investment to a public utilities commission by demonstrating that the investment is "used and useful," there must be confidence that a consistent market exists for the resultant product before a firm would invest in new generation capacity. In the case of nuclear power, a reliable demand for baseload capacity must be apparent. The ideal solution may be to have a power purchase agreement in place for the sale of the electricity, at least for the early years of production. In the absence of a power purchase agreement, very high confidence in the projections for demand growth and market prices will be needed to support an investment.

Alternative Fuel Sources

Once the need for additional capacity is established, other fuel alternatives must be considered. Natural gas-fired plants have dominated recent additions to the U.S. generating market, and they are expected to be the primary competition for any advanced nuclear plants. Because fuel costs are the driving component to the total generating costs for natural gas-fired plants, the price of natural gas is critical to the competitiveness of advanced nuclear plants. Even in the absence of carbon restrictions, one reactor vendor has claimed that its advanced design can be competitive at gas prices above $3.50/mmBtu. Exelon preliminary analyses estimate that gas prices consistently above $5 to $6/mmBtu are needed for new nuclear plants to be competitive. Internal modeling of potential nuclear investments also suggest a strong sensitivity to fluctuations in natural gas prices. Increases in the order of $2/mmBtu have a significant impact on the economic returns.

Coal plant investments are somewhat comparable to nuclear investments in that they have similar upfront construction costs and 36 to 48-month construction periods, as opposed to natural gas plants that have cheaper and shorter construction periods. These factors impose a drain on investor earnings as there are considerable expenditures during an extended period with no offsetting revenue stream. For 2002, the average nuclear production costs of 1.71 cents/kWh were just slightly less than those of coal plants which were 1.85 cents/kWh. Where nuclear and coal investments could diverge significantly is in a carbon-constrained regulatory environment. Corporate commitment to environmental stewardship coupled with financial recognition of avoided carbon emissions from nuclear plants would make nuclear power a more attractive investment.

Current Plant Issues

The likelihood of future nuclear investment depends heavily on the performance and issues of the current nuclear fleet. Continued solid industry performance is essential to maintain the confidence of both the public and the regulators. Issues challenging the current plants such as plant security and spent fuel disposal will need to have a clear path to resolution in order to reduce the uncertainty associated with the next generation of plants. With respect to security at nuclear plants, the NRC has issued numerous Orders to its licensees since the September 11, 2001 events. The objectives of these Orders will also be applicable to new plant designs. The advanced reactors will also be required to protect against the NRC-defined design basis threat for the facility.

With respect to spent fuel disposal, the Nuclear Waste Policy Act of 1982 and its subsequent amendments require or authorize the Department of Energy (DOE) to locate, build and operate a deep, mined geologic repository, and to develop a transportation system that safely links nuclear power plants, interim storage facilities and the permanent repository. Yucca Mountain in the Nevada desert was selected as the site for the permanent repository; however, the state of Nevada has objected to this selection, and has aggressively opposed the process set forth to demonstrate the adequacy of the site. Before any new nuclear investments are made, measurable progress will be needed to signal the likelihood of success in establishing the Yucca Mountain site as the final waste repository. Additionally, it should be noted that the Yucca Mountain project is envisioned to be the *first* spent fuel repository. Its capacity was established based on the expected spent fuel from the existing fleet of reactors. Any new reactors will need to re-address the issue of spent fuel disposal, hopefully by leveraging the eventual success of Yucca Mountain.

Regulatory Predictability

A stable political environment and a predictable regulatory process are needed so that licensing costs and duration can be accurately accounted for in investment evaluations. Additionally, the lack of regulatory predictability may adversely impact the financing terms for new nuclear capital projects. The NRC revised its previous process to separate the review of the proposed site from the review of the proposed design. The Design Certification process addresses design adequacy, and the Early Site Permit (ESP) process addresses the adequacy of the proposed site for the reactor. Exelon is one of three power companies who are currently pursuing ESP's for existing nuclear sites, with the intent to "bank" these sites for possible use in the future. The DOE is funding the three ESP projects on a 50/50 cost share basis. The Design Certification and ESP results would then be incorporated into the Combined Operating License (COL) process that authorizes actual construction and operation of a nuclear plant.

With the Design Certification process being exercised by reactor vendors, and the ESP process being demonstrated by three power companies, the component left is the COL process. There are no entities actively seeking a COL at present. To address this gap, the Nuclear Energy Institute (NEI) formed the Advanced Plant Task Force whose objectives include developing an efficient process for the preparation and review of COL applications and developing a predictable process for the construction inspection program. Exelon is an active participant on this task force, which includes frequent interaction with the NRC staff to address the regulatory process issues.

While the results of the Advanced Plant Task Force will be valuable to a future COL applicant, they do not replace the experience gained by the actual preparation and submittal of a COL application. Given the current financial and market environment, there is not a strong incentive for a single power company to be the "first mover" with a new nuclear investment. A group of leading power companies might consider forming a consortium to build and operate an advanced nuclear plant. The goal of this project would be to fully demonstrate the regulatory process as well as validate the construction and operating assumptions. Participation in such a project would require acceptable conditions and returns for the individual power companies.

Environmental Recognition

The environmental benefits of nuclear energy are often mentioned in policy discussions regarding electricity production and the environment, but these benefits are not reflected in any market mechanism that provides financial recognition to nuclear power. These programs were designed solely to achieve reductions in pollution from emitting sources. They do not recognize the role of technologies such as nuclear, hydropower and renewable energy that avoid pollution. In order to preserve the nuclear option, it is necessary to level the playing field for all forms of electricity production. A possible approach to recognizing the environmental benefits of nuclear and other non carbon-emitting forms of generation is to tighten controls for all major pollutants such as nitrogen oxides, sulfur dioxide and mercury; and to adopt controls for carbon dioxide. All forms of generation should be considered in meeting any additional requirements. Implementation of any changes to pollution controls would require a reasonable transition so as to avoid any undesirable supply disruptions.

New nuclear investments also could be encouraged through financial mechanisms similar to those used for other forms of non carbon-emitting generation, such as the existing production tax credit for wind and biomass. Other options include the implementation of an investment tax credit to encourage electricity generation investment by offsetting a portion of the earning dilution typically experienced during construction of capital-intensive projects.

V. Conclusions

Along with other forms of electricity generation, nuclear power is a critical component of the current U.S. energy strategy, providing approximately 20% of the country's electricity. Its unique attributes, highlighted by it being a carbon-free generation source, coupled with the expected increase in demand for electricity suggest that it is a generation option that should be preserved for the future. In order to revive industry investment in new nuclear facilities, actions must be taken now to address and improve upon key areas including reactor design, regulatory predictability and environmental recognition. Some work is in progress by the industry, but ultimate success will require a national energy platform that clearly recognizes the contribution of nuclear power and the actions needed to preserve it.

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[1] "Capacity factor" is defined as the ratio of electricity generated to the energy that could have been generated at continuous full power operation for the stated period of time

[2] "Rated output" refers to the power available at a specified power plant under specified conditions of operation.

policy

Renewables

technology

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Renewable Energy Options – An Overview

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A Renewables-Intensive Energy Future

Stabilizing future atmospheric carbon dioxide (CO_2) from fossil fuel burning is a Herculean task, requiring continuous and increasing buildup of new carbon-emissions-free power along with improvements in energy conversion efficiency over this century. Renewable energy from the sun, wind, water flows and biomass can provide carbon-emission-free power as long as the sun shines and the earth's biosphere lives. Prior well documented studies show that a CO_2 -emission-free primary power equivalent of 10 – 30 TW could be needed by 2050 to simultaneously mitigate against the most adverse climate change impacts from global warming and meet the energy needs that would allow for continued global economic growth of 2-3% per year—this being the most likely range in light of presently understood uncertainties (Hoffert et al, 2002; Caldeira et al., 2003). In round numbers, the rate of total global primary commercial energy consumption at the beginning of the century was approximately 12 TW. In other words, some 100 to 300 percent of present-day power might be needed from non-CO_2-emitting sources fifty years hence to significantly slow global warming.

Electricity is a rising fraction of total energy in the United States and worldwide. Producing a significant proportion of electricity in a GHG-emission-free manner is a major challenge. Renewables (mainly solar and wind power) are one path to responding to this challenge. The renewable path is technologically challenging, particularly implementing it in time to significantly slow global warming. But all alternate energy technologies to fossil fuel burning with CO_2 vented to the atmosphere face major hurdles. And if successful, renewables could provide the energy for our civilization sustainably and pollution-free into the indefinite future. This paper explores the potential for a significant scale-up in the use of renewables to produce electricity, with an emphasis on transmission and storage needs and options. Electricity, a clean, high quality energy product, is an increasing fraction of energy end use. For a typical conversion efficiency of 33% to convert primary energy (in chemical and nuclear bonds) to electrical energy with conventional fossil and nuclear fueled power plants and transmission lines, a fully electric economy might need only a third as much electric power as primary power; that is, 3.3 to 10 TW(e)[1], rather than 10 to 30 thermal terawatts, to slow global warming by 2050.[2]

Even so, getting 3.3 to 10 TW(e) electrical power capacity by 2050 from emission-free sources is a huge job, equivalent to building 1.2 to 4 conventional one-thousand megawatt power stations every week for the next fifty years starting immediately. Another way to view the scale-up needed is to consider that generating 3.3 TW (e) from solar cells at the earth's surface would require an area of roughly 220,000 km^2, equivalent to an array of PV panels 470 km on a side (Hoffert et al., 2002). But all the PV cells shipped from 1982 to 1998 would only cover less than 10 square kilometers. The gap between where we are and where we need to be is so large that it will, in the author's opinion, take efforts on the scale of the Apollo moon program or the Manhattan atomic bomb project to bridge it.

To minimize adverse impacts on biodiversity and human health from pollution and global warming, environmentalists have called for renewable electricity, and hydrogen made with renewable energy, since the "energy crisis" of the 1970s. So far, an insignificant fraction of U.S. and global energy supply comes from renewables. This is measurable in different ways. For example, the cumulative global energy produced by wind power by 1995 was approximately 0.3% of the electrical energy consumed by the United States in one year (Fig. 1, IEA, 2000). Worldwide in 2000, solar, geothermal, wind, combustible renewables, and burning garbage and other wastes collectively only provided 1.6% of electricity production (Malsch, 2003; (firewood burning in traditional societies, and hydropower, near saturation at a few percent of the total, are excluded)). A scale-up of renewable power from 1.6% to 10% or more in a few decades, and then to a major fraction of world energy supply by 2050 will be a major effort. The author argues that it's doable, but unlikely to happen spontaneously through market forces. Policy incentives are needed. The year 2050 is closer in time than the first nuclear reactor built by Fermi's team at the University of Chicago (2 December 1942), and fission today provides less than 5% of primary power. So the critical questions are: "How much power can the United States expect from renewables fifty years from now if we made it a priority?" and "What policies can get us there?"

So far, the U.S. Department of Energy (DOE) hasn't assigned renewable energy a significant role in global warming mitigation. DOE is, however, exploring two other paths: (1) centralized coal-fired power plants producing electricity and/or hydrogen, with carbon sequestered as pressurized CO_2 gas in depleted natural gas reservoirs or deep saline aquifers (the "FutureGen" project); and (2) new generations of nuclear reactors resistant to accidents and weapons proliferation with more sustainable and acceptable fuel cycles (the Gen III and Gen IV fission reactor programs). However, the GHG-emission-free energy challenge is so unprecedented that more technology initiatives are urgently needed. Expert panels and eminent scientists, haven't been very effective historically at predicting technology winners and losers. The most prudent policy is to imaginatively explore multiple approaches to insure that failures (normal in engineering development) aren't catastrophic. This group of authors argues that a new R&D initiative is urgently needed aimed at the technologies needed to generate and support the transmission and use of a significant amount of GHG-emission-free electricity from renewable energy by mid-century.

Total electric power consumption in the United States at the end of the 20th century was about 9.0 exajoules(e) per year (WRI, 1998, Table 15.1) equivalent to a mean consumption rate of 0.285 terawatts(e). Since there are about 8760 hours in a year, U.S. electricity consumption can also be expressed as 2,500 terawatt(e)-hours per year. At a plausible growth rate of 3% per year, U.S. demand by mid-century would be some 11,000 terawatt (e)-hours per year. How will this be met? Roger Anderson advances the case for new smart, next-generation, continental-scale electrical networks[3] that efficiently interconnect a wide variety of sources to consumers. These sources would include gas, coal and nuclear generation along with wind, solar, geothermal and other renewables in both centralized (deserts, offshore) and distributed (house, block, community, business, town) facilities. Predominantly wind or solar power electricity systems, whether grid-connected or not, will likely require enough energy storage capacity for days to perhaps a week.

Much can be achieved through expanded use and evolution of existing technologies, but in spite of dramatic cost declines for solar and wind technologies, these generation technologies for the most part remain more costly today than electric generation from fossil fuels, especially in the case of photovoltaics (solar cells). Moreover, large-scale deployment of these technologies depends on critical enabling technologies, particularly in storage and distribution (grid) systems designed to meet key renewable characteristics: intermittency, remote location, and extremely large numbers of generation sources. Addressing the storage, transmission, and distribution needs of renewables will require cost reductions in, and testing of, “smart” grid technologies in pilot and demonstration projects, and significant technological breakthroughs, or will utilize technologies that do not yet exist. Technologies critical to large-scale deployment of renewables need to be invented, mass-produced, commercialized and marketed.

Present Status and Outlook of Renewable Technologies

A long-standing controversy exists in the renewables community over centralized (often remote) versus distributed (often local) power generation. The “best” solution is not yet evident, but it may well involve some combination of the two. Renewables are thin gruel. Their adoption will require innovative and effective technical approaches to deal both with the low average power density and the intermittent nature of solar, wind and geothermal sources. To address low power density, one general approach is to seek sites where the energy flow per unit area is higher than average. However, these sites are not usually located near to where the energy is needed. They might be winds in the Great Plains, or offshore, atop high buildings, even in the intense jet steams of the upper troposphere; relatively intense sunlight might be captured by PV arrays in deserts, in orbit outside Earth’s shadow cone, or on the moon. Large-scale use of such distant energy sources will require more intelligent and efficient grid systems.

Managing supply and demand imbalances due to the intermittency of wind and solar power sources can be accomplished by storage and by “net metering,” i.e., extracting grid power when local power sources are insufficient, and selling power back to utilities when there is excess. Existing distribution networks can accommodate this so long as renewables are a small fraction of the power flowing through the grid. The precise fraction at which present grids would become overwhelmed isn't well characterized, but it's likely in the range of 5 and 20% from renewables, depending on details. A smarter grid is going to be needed for a significant amount of electric power to come from renewables.

Most homes, buildings, and commercial businesses consume power at kW(e) scales, and yet at present most power is generated at scales of hundreds of MW(e). This mismatch stems from the historical focus on the apparent economies of scale of large power production and transmission. At the household and community scale a fundamental transformation in energy production and use is now possible if we are prepared to invest seriously in distributed power generation *and* intelligent efficient grid systems. Thus, proponents of distributed and remote renewable power alike cite Internet-like models for transmission and storage (Vaitheeswaran, 2003). The present status of generation, storage, and grid technologies is summarized below.

Generation Technologies

Renewable energy generation technologies have experienced dramatic technical and economic advances over the past several decades, and now stand at a point where they are already contributing significantly to energy and electricity production in a number of states, provinces, and nations. Over the next five decades solar and wind energy could provide well over one third of electricity demand, with biomass meeting another 20 percent (Herzog, *et al.*, 2001).

The most cost-effective renewable today is wind, although the best sites are often remote from users or offshore. Wind could supply a major part of U.S. and world electricity requirements were turbines sited at locations with the highest wind intensity. Advanced technology options for wind include siting turbines in high-altitude intense jet streams -- for example, as tethered autogiros where part of the wind energy supports the turbine at altitude; and the balance goes to electric power generation transmitted to the surface. Although wind is more cost-effective in the near term, solar offers a larger resource. Several advanced solar power ideas exploit the fact that the long-term average solar power per unit area is about 8 times higher in space than at earth's surface. Collecting this energy in geostationary orbit or on the Moon, and beaming electric power to the surface with microwave or laser beams, may be cost-effective someday if access to space costs fall sufficiently. These, and other high-risk, high-payoff renewable energy ideas, including advanced biofuels exploiting genetic engineering, should be explored seriously to understand their attributes and potential.

The table below compiled by the California Energy Commission compares approximate present-day costs of several electrical energy sources (CEC, 1996).

Table 1

Levelized Electricity Cost at Busbar (¢/kWe-hr) (1996)[4]	
Coal	4.8 -5.5
Gas	3.9 -4.4
Hydro	5.1-11.3
Biomass	5.8-11.6
Nuclear Fission	11.1-14.5
Wind (without federal production tax credit)	4.0-6.0
Wind (with federal production tax credit)	3.3-5.3

Windpower at the busbar is already cost-effective at the best locations, in the 3-5 cents per kilowatt(e)-hour range, and is the world's fastest growing energy source on a percentage basis, at 32% per year growth for the past five years. Globally there was over $7 billion in wind energy investment in 2002 alone, and worldwide capacity is over 31,000 MW. In Denmark and some regions of Spain and Germany, 10 – 25 percent of total annual electricity generated is from wind. Rapid growth of electricity generated by wind is likewise planned by many State governments in the United States. The symbolically important "Freedom Tower" planned for the World Trade Center reconstruction is expected to contain wind turbines in its cable-tensioned upper structure sufficient to generate 20 percent of the building's electricity. Wind turbines have undergone a technological revolution in blade and motor design, and in the size of individual units. Five years ago 750 kW turbines were considered large, but today 1.8 – 3 MW machines are standard in new wind farms, with even larger machines (~ 5 MW) planned for many offshore installations. Innovations have come at such a rate that repowering (replacing/upgrading) existing wind farms installed within the last decade has become the industry norm.

Busbar electricity costs from photovoltaics (PV) are likewise declining. For many new technologies, costs decline with increasing market volume (and increasing time). Shown below as log-log plots for renewable and nonrenewable energy technologies are busbar electricity generation costs in 1990 Eurodollars per kilowatt-hour versus cumulative production in terawatt-hours (IEA, 2000). Numbers in parentheses are cost reductions in recent history from doubling cumulative installed power. When, for example, the size of PV markets doubled, the cost of PV electricity dropped to 65% of its previous value. Present PV levelized electricity costs are in the 15-25 cents per kilowatt(e) range, and continuing to decline.[5] Unit costs of massively scaled-up arrays are projected by the National Renewable Energy Laboratory (NREL) PV Roadmap to be competitive by 2025.

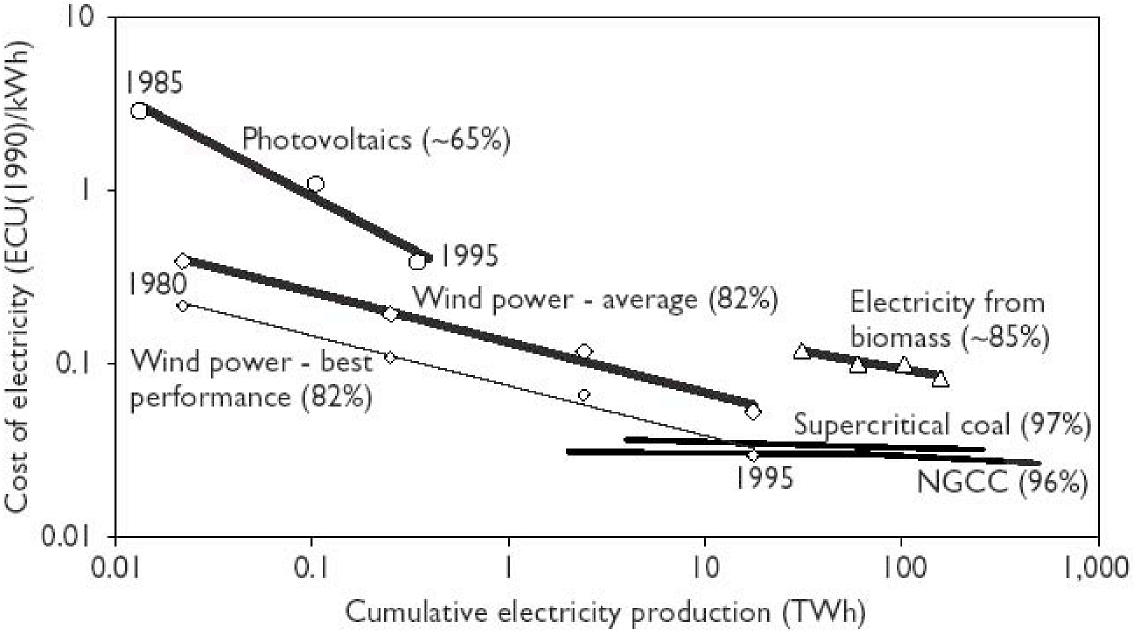

Figure 1. "Learning by Doing." Economies of scale for various electrical energy generating technologies thus far (from IEA, 2000).

Solar PV today relies on semiconductor-grade crystalline-silicon wafers that are expensive to produce compared with energy from fossil fuel sources. Less costly amorphous semiconductors, thin films, organic polymers and "quantum dot" technologies and mass-production manufacturing processes could provide major cost breakthroughs in world markets. These are under intense study. Radically new systems incorporating solar PV (and solar thermal) technologies, including solar power beamed from space, could likewise revolutionize the field by mid-century if they are aggressively pursued now. The potential of PV, and the magnitude of the solar resource, is too great to be deterred by presently high costs.

The biomass energy sector is also undergoing a significant transformation. Biofuels can be carbon-neutral if produced sustainably on energy plantations. For example, grasses and softwoods from managed energy farms can be burned alone or in combination with other fuels, or gasified and then co-mingled with other fuels such as natural gas. Efficient combustion of solid biomass is now practiced extensively in a number of countries such as Sweden where biofuels are expected to meet 20 percent of electricity demand by 2010 (Johansson, et al. 2002). Advances in biomass gasification that permit fuel substitution between natural gas and biofuels are now yielding commercial designs at kW to MW scales. Biomass can also be used as a source of hydrogen, which could play a critical enabling role in GHG reduction efforts because of its ability to serve as an energy carrier for both stationary and vehicle-based power. Unfortunately, and exacerbated by the low efficiency of photosynthesis (~ 1%), biofuels compete for land with carbon sequestration through forest conservation, with human agriculture, and with preservation of biodiversity. We need to understand these land-use trade-offs better and to explore advanced ideas like plants genetically engineered to be more efficient fuels, perhaps even producing hydrogen directly.

The Grid

At present, the grid is not even equipped to deal with the large increases in electricity traffic and congestion stimulated by the long-distance demands of power trading and restructuring of U.S. electricity markets. Slow response times of mechanical switches, lack of automated analysis of problems, and inability to "see the whole grid", are contributing to a noticeable increase in grid failures. These problems have caused a dramatic increase in blackouts and brownouts since 1998. They will propagate cascading grid failures more and more frequently unless we migrate to a new "smarter" grid control system because decision speeds increasingly are becoming too fast for humans to manage. In order to be able to utilize massive amounts of renewable energy sources -- accommodating centralized, large-scale, as well as smaller, distributed, home, business and community generation—it is necessary to first modernize the grid by installing digital controls, electronic switches, and higher capacity transmission lines. The management of the grid will require digital control, automated analysis of problems, and automatic switching capabilities more familiar to the Internet (like the routers sold by Cisco that break messages into packets and send them over several different routes to relieve congestion, only to reassemble them at the destination into your next e-mail). In short, the present U.S. electric grid will not work on any scale – local, state, national or international—at the higher loads and more diverse generation sources required in the future.

Storage

Most renewable energy sources are intermittent, variable, and unpredictable. Large-scale storage of electricity to accommodate the erratic nature of green power sources will be required. Electricity is not usually stored *per se*. Energy storage technologies instead convert electricity to other energy forms (gravitational, pneumatic, kinetic, or chemical). The lowest cost energy storage technologies avoid most of the cost of energy storage capacity by relying on natural geologic formations to store energy in elevated water or compressed air, the cheapest substances known. Unfortunately the scale and location-specific nature of energy storage in natural formations is likely to render it of limited benefit to small-scale distributed renewables. Available pumped hydro and compressed air energy storage (CAES) capacities could prove small in relation to the overall amount of future global renewable electricity—and attendant storage requirements—necessary for massive reductions in greenhouse gases. If energy storage in existing natural formations turns out to be insufficient, then man-made energy storage systems will be needed to support massive deployment of intermittent renewables.

Among man-made energy storage systems, the most well known is the battery. Batteries are very modular and are therefore technically well suited to use with small-scale distributed renewables. The chief difficulty of battery technology is short life which, given their capital cost can make storing electricity in batteries at least as expensive as generating electricity. Additionally, in the context of deep GHG reductions, the sheer scale of raw material needed for batteries (billions of tonnes) would likely outstrip the known reserves of common battery materials (lead, nickel, cadmium), further increasing battery cost. Such huge quantities of battery materials might also need to be recycled nearly indefinitely to minimize disposal issues and environmental impacts.

An emerging alternative to batteries is the high-speed flywheel. Flywheels store kinetic energy in a cylindrical or ringed mass, spinning at very high speeds (~10,000-20,000 rpm). Key issues for flywheels are safety and cost. Addressing the safety of deploying millions of flywheels would likely require underground use and/or stringent containment designed to withstand high-speed (~ 1000 miles per hour) fragments from a broken flywheel. This will likely place a lower limit on flywheel system capital costs. Performance has improved dramatically over the last two decades with progress in ultra-high strength composite materials. If future developments reduce the cost of ultra-high strength materials, flywheels will be substantially more attractive. Currently, flywheels are just beginning commercialization for high-value uninterruptible power applications. If they become economic in a renewables context, flywheels are likely to be best employed for routinely (i.e., daily) storing small amounts of energy delivered at high power for short times (1-2 hours),[6] or perhaps to smooth out peaks in power demand into and out of a much larger battery storage system (improving battery life).

Predominantly solar or wind power systems will likely require energy storage for days to approximately a week. If so, conversion of electricity to chemical energy is potentially attractive since chemicals are inexpensive to store. The most attractive chemical for this process is likely to be hydrogen (H_2). A predominantly renewable electricity supply could be combined synergistically with a future H_2 transportation sector. Co-production of electricity and H_2 fuel would enable massive deployment of intermittent electric generation by making efficient use of otherwise almost unavoidable excess generation during some time periods. Hydrogen storage onboard vehicles, be it in high-pressure gas, cryogenic or metal hydride tanks, is a major technological challenge to be solved before hydrogen cars can become widely accepted in the market. However, if this problem is solved satisfactorily, enough H_2 could be stored in the H_2 infrastructure and/or onboard H_2 vehicles to buffer H_2 demand on the time scale of days.[7]

Technology and Policy Paths Forward and Barriers

Research & Development

The United States hasn't had a pro-active research, development, demonstration, and deployment policy for renewable energy since the 1970s when Middle East oil cutoffs and OPEC price hikes were existential realities. Initiatives from that period include the Public Utility Regulatory Policy Act of 1978 (PURPA) mandating that electric utilities buy energy from independent generators (Grubb and Meyer, 1993). Cost-effective wind farms at the Altamont Pass near Livermore, California, a legacy of that period, would likely be nonexistent without PURPA and tax subsidies initiated by then Governor Jerry Brown. The DOE National Renewable Energy Laboratory (NREL) is potentially a key player in an expanded role for renewables. However, and despite important work on wind turbines, geothermal energy, PV, solar thermal, biomass and hydrogen, NREL so far is working on renewables mainly for niche markets. Absent U.S. federal incentives, policies supportive of renewable energy are coming mainly at the state level in the United States and from Europe (Hassol and Udall, 2003).

Research and development (R & D) is critically needed in each technology area discussed above. This should include large-scale demonstrations of system viability and shakedowns in operational environments to accelerate commercialization by lessening risks to investors of new technologies. Generation technologies require R & D for cost reductions and efficiency increases; grid technologies need R & D to reduce costs, in addition to testing sites for integrated operation of a smarter, digitally controlled, high-speed, “internet” type system. Storage technologies need R & D both to reduce costs and to increase the efficiency of renewable generation through integration with transportation sector energy needs. A critical failing in current U.S. R & D is the fickle and intermittent nature of renewable energy research and development support. Many R & D programs have exhibited roller-coaster funding cycles, at times doing more harm than good to the sustained development and deployment of specific technologies (Margolis and Kammen, 1999). At the same time, the R & D portfolios we have adopted for many renewable energy technologies have been tremendously risk-averse—and hence potential benefit-averse.

Research, development and demonstration programs designed to achieve a massive scale-up of renewable power from approximately 1% presently to 10% or more in a few decades to a major fraction of market share by century’s end are urgently needed. The need for a revolutionary change in the U.S. and global energy system to implement the goals of UN Framework Climate Change is accepted (in principle) by DOE and by the present administration—despite withdrawal of the United States from the Kyoto Protocol. In a December 11, 2003 letter to the *New York Times*, John H. Marburger III, President Bush’s Science Advisor, and Director of the White House Office of Science and Technology Policy, said:

> Although we believe that the Kyoto Protocol on climate change is flawed because its targets are arbitrary and expensive, the United States is demonstrating leadership and commitment on multilateral efforts . . . Investment in carbon sequestration, hydrogen fuel cycle technology, next-generation nuclear fission, fusion energy and energy-related biotechnology is an absolutely indispensable

precondition for an economy with dramatically reduced greenhouse gas emissions.

This group of authors supports these efforts. However, for reasons discussed in detail above, we urge that a "Third Stream" in renewable energy be included in the U.S. Climate Change Technology Program along side existing R&D streams in (1) hydrogen from coal with carbon sequestered and (2) advanced nuclear reactors. It is critical to explore the role advanced renewable energy technologies could play in time to slow global warming. The following specific program elements are excellent starting-points:

(1) **Continental and global-scale systems analysis of electricity and hydrogen transmission and storage and distribution systems**. This is in the spirit of "systems integrations" studies in the aerospace industry. Most energy technology research is focused on devices, but we need to explore physical limits and opportunities for global energy systems. A relevant principle of systems analysis is that optimizing a component of a complex system doesn't necessarily optimize the system as a whole. This idea needs to be applied to analysis of large-scale energy systems, for example, to explore the relative advantages and disadvantages of distributed generation versus long distance power transmission on a large scale.

(2) **"Smart" and low-loss electrical grids**. Electrical networks in the U.S. and Europe are going to be reconstructed or upgraded in any event in the wake of recent power outages. We should take this opportunity to see how they can be made user-friendly to renewable power sources. This needs to be studied now, to prevent foreclosing a major role for renewable electricity in the future. Reducing the electrical resistivity of such grids with high-temperature superconductors or carbon nanotubes is one element of this; computerized load management is another. Energy storage is important enough to have a program of its own.

(3) **Electrical and hydrogen chemical energy storage**. Buffering the energy produced by solar and wind is a critical issue for renewables to become cost effective at a large scale. The level of storage needed is massive, and could be the most expensive and technically challenging part of the system.

(4) **Advanced biomass**. Conventional biofuels aren't going to produce much emission-free power because the efficiency of photosynthesis is low (leading to large land use) and significant energy and nutrient inputs are needed. In principle, genetically engineered plants could, for example, produce hydrogen.

(5) **Space solar power**. Here is a real opportunity for DOE to get into a sustainable emission-free energy source with enormous potential. Beginning 40 years ago or more, DOE bet on controlled fusion power, a technology that looked doable. Using fusion in a controlled way to make electricity turned out to be

> much harder than anticipated. In principle, space solar power (SSP) can capture the sun's power more efficiently that terrestrial collectors, and moreover do the same job as fusion power plants—supply baseload electric power in arbitrarily large amounts anywhere on Earth. The United States has spent peanuts on this technology compared to tens of billions on fusion power. Arguably, we would be much further down the path to sustainable electric power had we pursued SSP at comparable funding levels. We have a second chance to explore this path now.

As a general principle, energy production and efficiency goals and openness to promising new ideas, not specific programmatic or technological subsidies, should guide the long-term direction of renewable energy R&D. One possibility is to create a DARPA-like organization whose program managers are charged with developing to technical maturity potentially revolutionary ideas, whatever it takes. DARPA (Defense Advanced Research Projects Agency) has a track record of doing this, having funded among many other technologies the Internet and supercomputers. Comparable efforts such as the modernization of, and renewable access to, national electricity grids are needed within DOE.

The Near Term (Now to 2025)

At present a Renewable Portfolio Standard (RPS)[8] is the most effective mechanism to bring renewable energy generation technologies to market. In the near term an RPS is an innovative and critically important measure because it utilizes a transparent regulatory policy to open markets for clean energy technologies. If a given energy technology has a 1 percent or smaller market share, its economics are dominated by a niche application, or by a specific regulatory provision. By contrast, roughly a 10 percent market share is one that is, for many technologies, one of economic competitiveness. The threshold to move from niche to mainstream is thus likely somewhere between 1 and 10 percent. An RPS provides one clear mechanism to move these promising but marginalized technologies to the point where they can compete in the broader marketplace. At present wind is the cheapest form of renewable energy in many locations, so care needs to be exercised to open markets to a range of renewables, as in Nevada where the RPS includes a specific set-aside for solar energy. Allowing regional differentiation could also be a significant benefit, so that biomass-rich regions such as the Southeast or Midwest could adopt initial set-asides for biomass-based renewable fuels. Related measures are introducing carbon credits into energy markets, and 'feebates.' Credits based on units of clean, carbon-free energy produced would allow trading in markets where low-or no-carbon energy sales and use are rewarded. 'Feebates' are an attractive and under-used policy measure where a technology is rewarded with a rebate when it meets a specified standard, and taxed when it falls below this level.

Another immediate policy option is the mechanism that many researchers consider to be the most effective and economically efficient tool at our disposal: pollution fees. There is nearly universal agreement that the prices of fossil fuels far fall short of their social and environmental cost. The introduction of taxes to reflect these costs – which could readily be made revenue-neutral through compensating reductions in income tax – would be an efficient way to encourage cleaner forms of energy generation. A carbon tax of $10/ton – which would result in gasoline prices still far less than we see in parts of Europe today – could encourage a wave of clean energy research and market implementation.

In many respects the greatest hurdle that must be addressed to take advantage of the opportunities for small-scale renewables generation and concomitant efficiency improvements is the role of utilities. In most areas the present utilities see few attractive revenue opportunities through encouraging greater efficiency. In particular, distributed generation appears to be a simple loss of revenue to electric utilities. R&D programs, subsidies, and other incentives for local, clean generation merely steal or divert customers. Thus at present the U.S. utilities correctly see little benefit, and great expense, in investing in the infrastructure needed to make distributed power generation and use the norm.

Moreover, regulators do not allow utilities to recover the costs of purchasing some of the equipment critical to renewables through consumer electricity rates. Both significant storage capacity and new “power controllers” are needed. New power controllers would allow a dual power system, in which higher quality, more reliable power can be delivered at an added cost only to those consumers that need it, while lower-quality, less reliable, less expensive power could be delivered to the rest of us. Supplying and charging higher rates for high-quality power would provide added revenue, revenue needed to attract the private capital necessary to upgrade the long-distance transmission system so that it can accommodate vast new wind and solar “farms.” Presently, we all get the same high-quality, expensive power (99.999 percent of the time it is within a strict range of voltage and frequency, referred to as “five 9’s” in the power business). Identifying opportunities for utilities to profit from clean, local, power production is one area critically in need of attention.

Grid system test beds *must* be in operation within 10 years if we are to meet the power needs of the continent 20 to 30 years out. Such test beds would combine promising new technologies. Designing a smart grid is difficult to do if individual technologies are deployed in isolation. The grid cannot be experimented with “live.” We must be certain that the grid is capable of handling each new technology *before* it is deployed. It is not an option to connect new gadgets directly to the grid, and accidentally cause massive, cascading blackouts. The problem with creating such national test beds is that electric utilities have among the lowest R&D expenditures of all companies (Lerner, 2003). The federal government must recognize the electric grid as vital to our prosperity and national security and support the creation of several test beds to experiment with deploying new smart grid technologies on a large scale and in an integrated way. Such an effort, dedicated to modernization of the electricity grid, is needed within the DOE.

The Mid Term (2025 to 2050)

The U.S. electric grid will almost certainly be upgraded in the coming decades to address the dramatic increase in blackouts and brownouts in recent years (Lerner, 2003). But hasty decisions to "beef up" the hub and spoke networks which now form the base of the U.S. electric grid and which are unsuited to decentralized and distant sources could be hard to change after infrastructure investments are "sunk". Restructuring the grid needs to be done from a long-term strategic perspective. As upgrades proceed, it is important not to foreclose "smart" grid systems, systems that can deal with variable and unpredictable loads from renewables in addition to more traditional power sources. Upgrades should be designed to accommodate long distances (continental scales and beyond), high-voltage AC and DC transmission lines as well as local, distributed generation and storage. A "lean engineered" electric power system, one that will improve efficiency of transmission and distributions system by 50 percent or more is needed. The grid should incorporate computer control systems to simulate and dispatch imperfect loads, deliver "five 9's" of quality power only when and where it is needed, and accept renewable power without the need to build enormous new distribution and transmission capacity (Anderson, et al., 2004). The estimated price of this upgrade is in the $100 billion range.

Within twenty to thirty years, a high temperature superconductor/liquid hydrogen (HTS/LH_2) super energy highway recently proposed by EPRI and DOE might provide the clean and green energy in both electrical and chemical forms to power urban transportation and electricity needs simultaneously. This "Super Grid" could employ a high-capacity, superconducting power transmission cable cooled within a liquid hydrogen pipeline—the liquid H_2 in the pipe doing double duty as superconductor coolant and energy-carrier. It should in this time frame also be possible to produce solar cells with installed costs of around $1000 per peak kilowatt(e).

The Long Term (2050 and beyond)

The projected electricity demand worldwide is huge. In the United States alone, generating a major fraction of the 10 to 15 thousand terawatt(e)-hours per year projected for 2050 with solar and wind power is an enormous challenge. The gap between where we are and where we want to be is so large that it will take R & D efforts on the scale of the Apollo moon program or the Manhattan atomic bomb project to bridge it. This grand transformation will also require policy incentives, large-scale investment, mass production and innovative marketing. Still, our panel finds no physical limits, no "showstoppers" preventing renewables in principle from becoming major primary power sources.

The history of technology is replete with seemingly "far out" ideas that changed the world. But the track record of "expert predictions' of where specific technologies will go on century time scales is not encouraging. Consequently the most prudent policy is to imaginatively explore multiple approaches. The "Willie Sutton Principle"—robbing banks because that's where the money is concentrated—argues for going where and when renewable power is most available, even to very remote or centralized capital-intensive sources if they are cost-effective. Buckminster Fuller proposed a continent- and time zone-spanning global grid that could wheel solar electricity from the sunlit hemisphere of Earth to the night side, before the discovery of high temperature superconductivity that could enable it. Radically new technologies like collecting wind power from the jet stream, or ocean power from the thermocline,[9] or solar power from geostationary orbit or the Moon, could play a major roles fifty years from now.

In any case, solar cells are likely to be a lot less expensive by 2050. Amorphous thin-film alternatives hold promise, as do organic cells, with the potential for unprecedented low cost – well below $0.50 per peak watt. An alternate vision for renewable energy is distributed generation: each rooftop covered with cheap solar cells, each building complex or neighborhood with its own fuel cells and hydrogen storage.

The march of discovery and technological innovation goes on, a process the United States has been leading so far. Continuing this leadership will require a greater commitment to R&D and to science and technology education in the increasingly globalized world economy. We're living now off our prior investments. The potentially revolutionary discovery of high-temperature superconductive materials several decades back has ramifications for renewable energy that are still working themselves out. More recently, Rick Smalley's discovery of a new form of carbon, carbon nanotubes, is a wild card that, like personal computers and the Internet, could enable renewable energy in ways largely undreamt of today. Nano-scale transmission wires, called quantum wires (QW), might revolutionize the grid. The electrical conductivity of QW is higher than copper at one sixth the weight, and QW is twice as strong as steel. A grid made up of such transmission wires would have no line losses or weather dependencies, eliminating the need for massive emergency generating capacity. QW, perhaps spun into non-corrosive polypropylene-like rope, might be buried "forever" with no fear of corrosion and no need for shielding of any kind.

There have been those with upbeat technological visions since the Industrial Age, and we admit to being among them. But the future—as Arthur C. Clarke observed—is not what it used to be. As it evolves, we have an opportunity to shape it adaptively. There will be lags between cause and effect, and the window of opportunity to slow global warming may be limited. The challenge for *Homo sapiens* is implementing energy policies now that will foster the global environment we want for our grandchildren.

Conclusions

Where should The United States be in 50 years? This group of authors argues here that a major fraction of electricity can and should come from renewable energy. The more the better, but as a practical matter anything over 20 percent – twenty times more than today—will be useful in slowing global warming. An ambitious but desirable interim goal for climate change stabilization is 10 to 30 terawatts of CO_2-emission free primary power worldwide: one-third from fossil fuel with sequestration, one-third from advanced nuclear and one-third from renewables by 2050, with the U.S. amount perhaps 15% of the total. To get there we must start immediately to:

- Develop an appropriate R&D effort, likely on the scale of the Apollo Moon program or the Manhattan atomic bomb project or greater. Consider a DARPA-like program management model with a mandate to advance technology significantly beyond the state-of-the-art, to bring new options into the market place, and to fund a broad spectrum of researchers. This program would add a "third stream" to DOE's present two paths for reducing GHG emissions (carbon capture and sequestration, and a new generation of nuclear reactors).
- Get test-beds for smart transmission and distribution systems up and running.
- Expand the use of regulatory mechanisms, such as RPS, which serve to increase the market share for existing renewable-generation technologies, to bring costs down and to make renewables competitive with other technologies.
- Begin to insure that renewable electricity generation technologies are developed in coordination with building and transportation technologies (particularly the use of H_2 as a transportation fuel) with a view to finding synergistic opportunities including meeting renewable energy storage needs in the most efficient manner.
- Create a new generation of engineers and scientists, attracting top students to these fields through fellowships and scholarships.

It will also be critical to:

1. Find ways to make renewable and distributed generation financially attractive to utilities.
2. Obtain government or private market financing to supplement the extremely low R&D funding available within the electricity industry.
3. Avoid hasty decisions to beef up hub-and-spoke networks unsuited to decentralized and distant sources. The results of such decisions could be hard to change after infrastructure investments are "sunk" and it is important not to foreclose smart grids with sophisticated computerized load management.
4. Insure that support for renewable programs is steady and continuous

Twenty to thirty years out the United States should be targeting at least 10% of electric power from renewable energy sources:

- Build the next generation, smart electricity transmission and distribution system, possibly a "super grid" which would integrate the H_2 and electricity distribution systems with superconducting power transmission cables cooled within a liquid hydrogen pipeline.

- Install equipment that will allow a dual system so that high-quality power (e.g. "five 9's" of reliability) can be supplied only where and when it is needed, enabling users of high-quality power to be charged appropriate rates, and lower-grade power can be supplied to the vast majority of users at lower rates.
- Have renewable generation technologies become cost-competitive not just in niche markets but also widely across regions and at scales ranging from buildings through communities and large centralized plants and linked into a "smart" transmission and distribution system.
- Build up storage capacity either through integrating transportation and electricity systems or through storage technologies developed in the R & D program.

By 2050 at least 20 percent of power should come from GHG emission-free renewable sources:

- Low-cost renewable generation technologies utilizing the entire spectrum of resources: solar, wind, ocean, biomass, etc.
- New breakthrough approaches developed from technologies presently in early research states or as yet not dreamed of: bio-converters, solar power beamed from space, global power grids wheeling electricity from one side of the earth to the other, transmission wires based on nano-technology, a fully integrated, transportation and power generation system.

Getting there will require substantial R & D investments in renewable energy technologies—investments not yet being made at the required scale and focus. This work would be done by national labs, universities and industry, and could perhaps be part of the U.S. Climate Change Technology Program (CCTP). Research tasks would include continental and global-scale systems analysis of electricity and hydrogen transmission and storage and distribution systems, smart and low-loss electrical grids, (3) electrical and hydrogen chemical energy storage, advanced biomass and space solar power. Achieving this goal "…requires the recognition that, although regulation can play a role, the fossil fuel greenhouse effect is an energy problem that cannot be simply regulated away." (Hoffert et al., 2002). In the words of U. S. Energy Secretary Spencer Abraham (2003):

> We can set targets and timetables for reducing emissions by certain percentages by certain dates. …. We will also need to develop the revolutionary technologies to make these reductions happen. That means creating the kinds of technologies that do not simply refine current energy systems, but actually transform the way we produce and consume energy. When those technologies are developed, we will all exceed our targets.

The job of the science and engineering communities now is to develop strategic technology research programs capable of "transforming the way we produce and consume energy."

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[1] Units of power and work used here are: 1 W (watt)= 1 J/s (joule per second); 1 EJ (exajoule) = 10^{18} J; 1 TW (terawatt) = 10^{12} W; 1 EJ/yr (exajoule per year) = 0.0317 TW (terawatts) = 278 TW-hr/yr (terawatt-hours per year). Watts and joules from burning chemical (i.e. fossil) and nuclear fuel are unsubscripted. However, we use "(e)" to denote work and power in electricity.

[2] This somewhat underestimates electric power needed, since space heating, for example, normally consumes as many electric as thermal watts because the energy is dissipated as heat.

[3] The present grid is primarily a "hub-and-spoke" system, with generation facilities and their attendant transmission and distribution systems originally built to serve local regions. These "hubs-and-spokes" have been partially brought together into three "interconnects," one serving the eastern two-thirds of the United States and Canada, one serving most of Texas and one serving most of the rest of the Canada and the United States.

[4] Electricity cost at busbar is the average cost of generation including capital investment amortization, operating costs, and fuel over the plant lifetime. Busbar costs do not include transmission and storage costs.

[5] For distributed solar and wind power, busbar costs may not provide the most useful comparison with conventional power sources because distributed solar and wind avoid transmission and distribution costs which must be added to busbar costs in the case of conventional power supply.

[6] Flywheels are not suited to long-term storage because momentum, on which they are based, is lost over time.

[7] When wind or sunshine were low, higher H_2 prices might temporarily reduce H_2 demand from vehicles. Later, when solar and wind electricity supplies returned to higher levels, accumulated demand for H_2 fuel could be met and H_2 prices could drop.

[8] A Renewable Portfolio Standard specifies that a certain amount of electricity must come from renewable energy. In some states, utilities may comply with an RPS through the use of renewable energy credits.

[9] A thermocline is a layer which separates regions of water that are of different temperatures within large bodies of water. Presently available technologies such as such as Ocean Thermal Energy Conversion (OTEC) take advantage of this temperature gradient to make electricity. See http://www.nrel.gov/otec/what.html.

Renewable Energy Options for the Emerging Economy:
Advances, Opportunities and Obstacles

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A Renewables-Intensive Energy Future

Renewable energy technologies have experienced dramatic technical and economic advances over the past several decades, and now stand at a point where they are already contributing significantly to energy and electricity production in a number of states, provinces, and nations. Over the next five decades solar and wind energy could provide well over one third of electricity demand, with biomass meeting another 20% (Herzog, *et al.*, 2001). Combining this potential growth with nuclear systems that currently provide 20% of U. S. electricity, and with an acceleration of the current 1 – 2% annual rate of decarbonization and efficiency improvements, our energy system could look very different in 2050 than it does today. In sum, these technologies – all largely available today, or in the near term – could readily provide a total of 70% or more of electricity from carbon-free sources—*even for a future requiring significantly more energy than the current global supply capacity of ~10 TW demand*. A commitment to energy R&D efforts, distributed energy capacity, energy storage and market-support policies could make this future a reality. This process would be greatly facilitated if economic and accounting practices were to evolve to value the full social and environmental costs of energy, services (Kammen and Pacca, 2004).

This vision of an economically, politically, and environmentally sustainable energy future depends critically on a commitment to improving market access today for low-carbon energy technologies to facilitate the dramatic growth of this sector. The central message of this paper is that this transition will require continued research and development, *but it can be achieved as an evolution from our current energy system*. To accomplish this the markets for solar, wind, and biomass energy must be dramatically expanded, and power transmission and storage systems must be overhauled to permit distributed energy management to interface with regional grids. This transformation, while entirely possible, will take a level of leadership and energy integration that we have realized to date only in brief fits and starts. A commitment will be needed to national energy security, and to international leadership in clean energy technology development and deployment.

Technological and Market Outlook for Distributed Renewable Energy Systems

Wind energy is the world's fastest growing energy source on a percentage basis, at 32% per year growth for the past five years. Globally there was over $7 billion in wind energy investment in 2002 alone, and worldwide capacity is over 31,000 MW. In Denmark, and some regions of Spain and Germany, 10 – 25% of total annual electricity generated is from wind. The north German state of Schleswig-Holstein currently meets 25% of annual electricity demand with 2,400 wind turbines that have a total capacity of 1,800 MW. Wind in Schleswig-Holstein has met over 50% of demand for selected months during both 2001 and 2002. The state has committed to achieving 50% of electricity from wind by 2010, and is currently embarking on biomass and hydrogen energy programs as well (http://landesregierung.schleswig-holstein.de). Not only have wind turbines undergone a technological revolution in blade and motor design, but also in scale. Five years ago 750 kW turbines were considered large, but today 1.8 – 3 MW machines are standard in new wind farms, with even larger machines (~ 5 MW) planned for many off-shore installations. Innovations have come at such a rate that repowering (replacing/upgrading) existing wind farms installed within the last decade has become the industry norm.

In spite of the limited market access and spasmodic R&D support that renewables have received, we are in a period of significant technical and economic evolution. Global production of photovoltaic cells has surpassed 500 MW/year, and has seen sustained growth of roughly 20%/year. With current costs of ~ $5/W for fully installed systems, a variety of studies forecast that within the next decade costs could decline to $1.50/W (see, e.g. Duke and Kammen, 1999), a critical cost range at which PV would be widely competitive with other technologies, as opposed to the current situation in which solar power is attractive primarily in niche markets and in areas with specific, favorable market policies (e.g., California where a 45% rebate exists for grid-tied residential systems). The rate of research and patenting in the solar industry has increased significantly recently, with exceptionally promising technological developments in the areas of thin films, conductive plastics, and now organic photocells.[1]

The biomass sector is also undergoing a significant transformation. Biomass is estimated to have the potential to meet 20 - 25% of global energy needs, and can be used to meet a combination of electricity, heating, and transportation needs. That said, significant air quality, and land-management issues need to be addressed to achieve this potential[2] (Cushman, *et al,* 2001). Biomass, most likely grasses and softwoods can be combusted directly or gasified and burned, either alone or together with other fuels such as coal or natural gas. Efficient combustion of solid biomass is now practiced extensively in a number of countries such as Sweden where biofuels are expected to meet 20% of electricity demand by 2010 (Johansson, et al., 2002). Advances in biomass gasification that permit fuel substitution between natural gas and biofuels are now yielding commercial designs at kW to MW scales. The fact that biomass, if managed correctly, can be available on demand, i.e. as a fully dispatchable energy source, makes it even more valuable in a renewables-intensive future. Biomass can also be used as a source of hydrogen, which could play a critical enabling role in GHG reduction efforts because of its ability to serve as an energy carrier for both stationary and vehicle-based power.

At the household and community scale a fundamental transformation in energy production and use is now possible if we are prepared to invest seriously in distributed power generation *and* intelligent efficient grid systems that operate under markets that reward clean power. Most homes, buildings, and commercial businesses consume power at kW scales, and yet most power is generated at scales of hundreds of MW. This mismatch stems from the historical focus on the apparent economies of scale of large power production and transmission. The prevailing mode of power generation and distribution assumed that larger and larger power plants, generally 1,000 MW at minimum, were the preferred unit of production thermodynamically and economically. This was due to a number of factors, but can be summarized as a product of the utility monopoly model and the pursuit of technologies for larger and larger scale power plants, to the exclusion of research on alternate technical and economic models. Today 50 – 80 MW gas turbines are more energy efficient than units an order of magnitude larger, and virtually no economic analysis or real-world testing has take place to evaluate other energy management models. In particular, economic systems that reward energy efficiency and conservation, and local clean power production have never been coupled with sustained research programs on building-scale power production, storage, and management through truly 'two-way' grid connections.[3]

Combined heat and power systems—now recognized and supported in many nations and by a new U.S. Department of Energy CHP initiative[4]—hold promise to increase the effective efficiency of a range of fossil-fuel technologies by roughly 40% to over 60% through the capture and use of waste heat. CHP is primarily dependent on intelligent regional planning where facilities requiring heat are co-located or linked to those producing excess. At the same time, regional planning could open markets for small-scale decentralized power generation, such as building integrated photovoltaic systems, electricity and heat production from fuel cells. Significant business opportunities exist for developed and developing country markets for highly efficient – even net energy producing – buildings. A powerful example is the recently completed renovation of the Moscone Center in San Francisco where a 675 kW roof photovoltaic system was installed at the same time as an overhaul of the HVAC system. Undertaking both projects as a package improved the economics of each component significantly.

Near-Term Policy Options

In keeping with the changes in renewable energy technologies, an increasingly diverse set of policy measures to facilitate the commercial introduction of large-scale use of alternative energy systems are now in practical use. Foremost is the Renewable Portfolio Standard (RPS), which has been adopted in different forms by 14 U. S. states, with commitments ranging up to 20% of total electricity by 2017 (California). In a significant recent setback, the 2003 Federal Energy Bill no longer includes a federal RPS, although some of the candidates for the presidency in 2004 still support such a policy. A recent U. S. Department of Energy study concluded that a 20% federal RPS by 2020 would save the country billions of dollars per year through reduced fossil fuel costs, increased investment in domestic jobs, and through reduced security costs to safeguard our access to overseas oil and gas.

In the near term an RPS is an innovative and critically important measure because it utilizes a transparent regulatory policy to open markets for clean energy technologies. At present wind is the cheapest form of renewable energy in many locations, and care needs to be exercised to open markets to a range of renewables, as in Nevada where the RPS includes a specific set-aside for solar energy. Allowing regional differentiation could also be a significant benefit, so that biomass-rich regions, such as the Southeast or Midwest, could adopt initial set-asides for biomass-based renewable fuels. Related measures are: introducing renewable energy or – or 'green'—credits into energy markets and 'feebates' to provide the economic tools to encourage clean energy production and use. Renewable energy credits—based on units of clean, carbon free energy produced, or for energy saved—allow trading in markets where low-or no-carbon energy sales and use are rewarded. ‘Feebates’ are an attractive and under-used policy measure where technologies—from stationary power plants and refrigerators, to vehicles—are rewarded with a rebate when they meet a specified standard, and taxed when they fall below it. ‘Feebates’ can be used to simultaneously reward sustainable systems and tax polluting ones, and can be ratcheted up to encourage continued innovation.

At the local level a variety of significant new policy instruments have emerged. The City of San Francisco approved a $100 million solar revenue bond in 2001 which will finance the installation of over 40 MW of peak capacity (MW_p) of photovolatics on city buildings and – most importantly – on cooperating local businesses and residences. The state of Hawaii, and a number of California municipalities as well as the European Community are in the process of adopting or are considering similar solar bond financing mechanisms. In Hawaii and Japan high cost for electricity have encouraged the introduction of solar, biomass, wind, and ocean-thermal energy systems.

Missing from this suite of immediate policy actions is the mechanism that many researchers consider to be the most effective and economically efficient tool at our disposal: pollution fees. There is near universal agreement that the prices of fossil fuels far fall short of their social and environmental cost. The introduction of taxes to reflect these costs – which could readily be made revenue-neutral through compensating reductions in income tax – would be an efficient way to encourage cleaner forms of energy generation. A carbon tax of $10/ton – which would result in gasoline prices still less than we see in parts of Europe today – would encourage a wave of clean energy research and market implementation.

Opportunities and Barriers

In the 2010 time-frame, a number of measures need to be continued, and a number of major issues need to be addressed to move the energy economy toward one with renewable energy utilized economically on a large scale.

In many respects the greatest hurdle that must be addressed to take advantage of the opportunities for CHP systems and local building-integrated renewables (primarily solar) and to focus greater attention on the value of efficiency is the role of utilities. In most areas the present utilities see few attractive revenue opportunities through encouraging greater efficiency, and in particular distributed generation appears as a simple loss of revenue. The opportunities for utilities to both encourage and to profit from clean, local, power production is one area critically in need of attention. As the conduit of electricity, utilities could become the entities that manage power transactions between houses, businesses, and industry that buy and sell in a real-time, distributed market. Beyond that, utilities themselves could transform the power industry by becoming an agent of regional planning entering into performance-based contracts[5] for both electricity efficiency and CHP transactions, and developing local energy storage capacity (pumped hydro, spinning reserves, flywheels, hydrogen/electricity stations).

At present the U. S. utilities correctly see little benefit, and great expense, in investing in the infrastructure needed to make distributed power generation/use the norm. R&D programs, subsidies, and other incentives for local, clean generation merely steal or divert customers from the utilities. Performance contracts based on clean power production and demonstrated energy savings by customers would be one way both to reward clean energy innovations and to make these programs economically attractive to the utilities.

Market Barriers: Market barriers to renewable energy technologies severely limit their ability to expand market share even when they are economically competitive on a technology-to-technology comparison. If a given energy technology has a 1% or smaller market share, its economics are dominated by a niche application, or by a specific regulatory provision. By contrast, roughly a 10% market share is one that is, for many technologies, one of economic competitiveness. The threshold to move from niche to viability is thus likely somewhere between 1 and 10%. An RPS provides one clear mechanism to move these promising but marginalized technologies to the point where they can compete in the marketplace. As examples, in the case of both photovoltaics and wind, multiple routes exist to move into this 'competitive' category. Both technologies can be deployed in stand-alone, distributed grid-connected, and central-station applications. R&D efforts for technology provide returns across all these scales. A second mechanism that should be employed is aggressive DG milestones, such as energy-autonomous buildings and appliances that, on average, produce as much energy as they consume.

Distributed Generation Research: DG systems hold great promise for tailoring the amount of power generated to local demands. To accomplish this a significant program of research is needed on smart-grid technologies to allow monitoring and flexible re-routing of small amounts of power surplus and demand. Building integrated power production could become the norm – with many buildings self-sufficient in energy supply from clean sources – but will require a new generation of grid hardware to make it practical. At the same time, new financial tools are required to make the support of DG attractive to utilities.

Making R&D A Sustained Priority: A critical failing in our current energy economy is the fickle and intermittent nature of renewable energy research and development support (R&D). Many R&D programs have exhibited roller-coaster funding cycles, at times doing more harm than good to the sustained development and deployment of specific technologies (Margolis and Kammen, 1999). At the same time, the R&D portfolios we have adopted for many renewable energy technologies have been tremendously risk-averse—and hence potential benefit-averse. In particular, our R&D programs for solar and fuel cell systems have not been focused on short- or long-term goals that we were committed to achieve, but instead to spend available funds, which often had to be justified on unrealistically short timetables. Energy production and efficiency goals, and not specific programmatic or technological subsidies, need to guide the long-term direction of our R&D portfolio.

Each of the technologies discussed above has critical R&D needs. For solar power, the needs are largely for efficiency increases and cost decreases in thin film technologies, and in the huge but unrealized potential of ultra low cost organic cells. For both wind and PV technology, power storage technologies would dramatically enhance their attractiveness. In hydrogen it is in both the cost and durability of fuel cell membranes, and in the cost of hydrogen production.

Technology, Practice, or Policy	Timing	Issues
Implement a federal Renewable Portfolio Standard (e.g. 20% renewables by 2010) and reward states that meet and particularly exceed this level. As part of this process, the job creation, environmental sustainability, and international security benefits of clean energy must be integrated into national economic planning.	Immediate	A RPS is presently the most effective mechanism to bring new renewable energy technologies to market, which in turn is the most effective way to foster additional innovation. Lack of experience with these technologies in large-scale power systems and reluctance to diversity the energy market are major roadblocks
Introduce Feebates and a Market for Clean Energy Credits	Immediate	Clean energy credits are hindered by the same issues noted above that impact the RPS. Feebates require oversight and enforcement.
Re-engage the U. S. in International Negotiations on Greenhouse Gas Reductions	Immediate	The precise form and requirement of the Kyoto Protocol are far less important than a *real* commitment to climate leadership (and further, great latitude exists for an engaged U.S. to shape the actual plan). The global community is crippled by lack of U.S. involvement.
Design a *Goal-Oriented* Clean Energy Policy. A reasonable goal would be to eliminate the need for overseas oil and gas import while reducing GHG emissions.	Immediate beginning; 20 years to fully implement new oil & gas policy.	Clean energy provides political and environmental security and stability, yet the few past efforts have focused on political or economic opportunities, not important targets.
Reinvent the U.S. electricity grid to facilitate local power generation and consumption in ways that make this new model attractive to utilities, and promote energy storage technologies	One to two decades; although investment should begin at once, this should be a gradual process	The estimated price of this upgrade is $100 billion, and current market practices do not reward this investment in infrastructure.

Regain global leadership in the development and sales of clean energy systems. Specific goals could include: • $1/W solar cells through a range of specific technologies • Global leadership in wind turbine sales • Develop biological hydrogen production on an industrial scale • Link energy and agricultural output goals with specific targets	One to two decades	There was extensive innovation in solar, wind, and fuel cell technologies in the U.S. over the past decades, yet through inaction the U.S. has lost its leadership position in many of these areas. Clean distributed energy is a growth industry that we should lead and reap the rewards, not lag.

What is remarkable in reviewing the clean, largely distributed energy options we now see entering commercial markets is the degree to which the bulk of our energy needs could come from low-carbon energy. The 70% or more reductions in carbon emissions that ecological assessments of climatic change now see as necessary is achievable. Critical to accomplishing this change is to recognize that we do not today know what energy mix we will likely want in 50 years, but that we do not need to either pin our hopes on exotic technologies, nor do we need to hope for miracles. The near-term policy options we have to open markets to current renewable energy systems will both clean and diversify our energy mix, and will provide the essential proof-of-market that the private sector needs to make clean energy a priority. Major areas of federal R&D support are needed, but the opportunity today to mix market mechanisms and sustained public sector support provides options that were until recently largely unrealized.

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[1] In an important series of technological advances, photovoltaic thin film and plastic solar cells, long of interest to the research community, have each been engineered to provide significantly higher efficiencies

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than seen over the past decade. Organic cells, with the potential for unprecedented low costs—well under \$0.50 per peak watt—are now being seen as a possibility. The R&D programs needed to bring these technologies to market will be substantial, and must be managed differently than past efforts where short-term politics and not adherence to challenging objectives have sadly been the norm. Specific goals, such as moving several PV technologies to the \$1/watt level, deserve a commitment akin to the Apollo project, or the efforts to sequence the genome.

[2] The possibility to provide energy capacity from biomass on this scale is disputed, and would require globally significant amounts of land area. Importantly, however, synergistic linkages between agricultural, silvicultural, and energy research efforts could make this goal more realistic.

[3] Politically, proponents of fossil fuel systems, renewables, and nuclear power have never worked together, and generally view the other technologies as competitors, or worse. As a result no real experience exists on the very great benefits of linking these technologies physically, such as in hybrid systems, or economically, in networks that recognize that short-term least cost pricing may result in very large long-term costs (such as the price California paid for dismantling the system of non-utility 'Qualifying Facilities' that during the 1980s consisted of small hydro, biomass, gas turbines, solar, and wind technologies that at one point provided fully one-third of the state power needs). This diverse, distributed, power network was the best example in U. S. history of the rewards in innovation and creativity that is possible when monopoly control of the power sector was lessened.

[4] The U.S. DOE established in 2003 a series of regional research and applications centers focused on CHP systems.

[5] Performance-based contracts allow parties to earn variable amounts of revenue based on the energy savings (performance) achieved. For example, a utility could enter into an energy-efficiency contract with a building owner or operator to reduce the energy demands of the building. Under such a contract, a building owner, operator or contractor would receive higher payments as energy use increasingly falls below an established baseline. For such contracts to gain acceptance by utilities, utilities would have to operate under a regulatory regime that enabled such arrangements to be profitable for all parties.

The Distributed Storage-Generation “Smart” Electric Grid of the Future

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By 2050, North America will need somewhere between 15 and 20 Terawatt hours/year of electric power (DOE/EIA estimate[1]). The storage, transmission, and distribution technologies of the smart grid of the future—a web-enabled, digitally controlled, intelligent delivery system—must be able to deliver that amount of power to all corners of the continent efficiently. Millions of generation and storage points, both remote and locally distributed, from many different energy sources will be needed to supply that amount of electricity. A continental-scale grid will be needed to interconnect remote gas, coal and nuclear generation with wind, solar, geothermal and other renewables, in both centralized (deserts, offshore) and distributed (house, block, community, business, town) facilities.

Such sources cannot be simply added to the existing grid – it is not smart enough. The management of the grid will require digital control, automated analysis of problems, and automatic switching capabilities more familiar to the Internet (like the routers sold by Cisco that break messages into packets and send them over several different routes to relieve congestion, only to reassemble them at the destination into your next e-mail). In addition, most renewable energy sources are intermittent, variable, and unpredictable. Large-scale storage of electricity to accommodate the erratic nature of such green power sources will be required in elevated reservoirs; in superconducting batteries, flywheels and magnets; and in underground compressed air and natural gas caverns [see also paper by Berry]. In short, the present U.S. electric grid will not work on any scale—local, state, national or international—at the higher loads and more diverse generation sources required in the future.

Why? At present, the grid is not even equipped to deal with the large increases in congestion and electricity traffic being stimulated by the long-distance demands of the new power trading and deregulation of U.S. electricity markets. Slow response times of mechanical switches, lack of automated analysis of problems, inability to “see the whole grid,” are contributing to a noticeable increase in failures of the grid. These problems which have caused a dramatic increase in blackouts and brownouts since 1998, will propagate cascading failures of the grid more and more frequently unless we migrate to a new “smarter” or more intelligent grid control system because decision speeds increasingly are becoming too fast for humans to manage. As demand, sources of energy, and distances between demand and supply increase, the grid will become increasingly vulnerable not only to blackouts set off by equipment failures and weather, but also to terrorist attacks.

In order to be able to utilize massive amounts of renewable energy sources, it is necessary to first modernize the grid by installing digital controls, electronic switches, and higher capacity transmission lines, within the next ten years or so.

10 Year-out Technology Needs

The northeastern United States blackout of August 14, 2003, was not an isolated event. With any complex machine like the electric grid, there will always be the occasional failure. Since 1998, the frequency and magnitude of blackouts has increased at an alarming rate, however, deviating from the stable, predictable "fractal" pattern of the previous 15 years.[2] Blackouts in Chicago, Delaware, Atlanta, New Orleans, and New York in 1999, San Francisco and Detroit in 2000, and the infamous California "problems" of 2001 deviated from the predictable behavior of the previous 15 years in the United States. When examining the frequency of outages against the number of customers affected by each, we should have perceived clearer warnings that the system was going unstable long before August 14, 2003 (Figure 1).

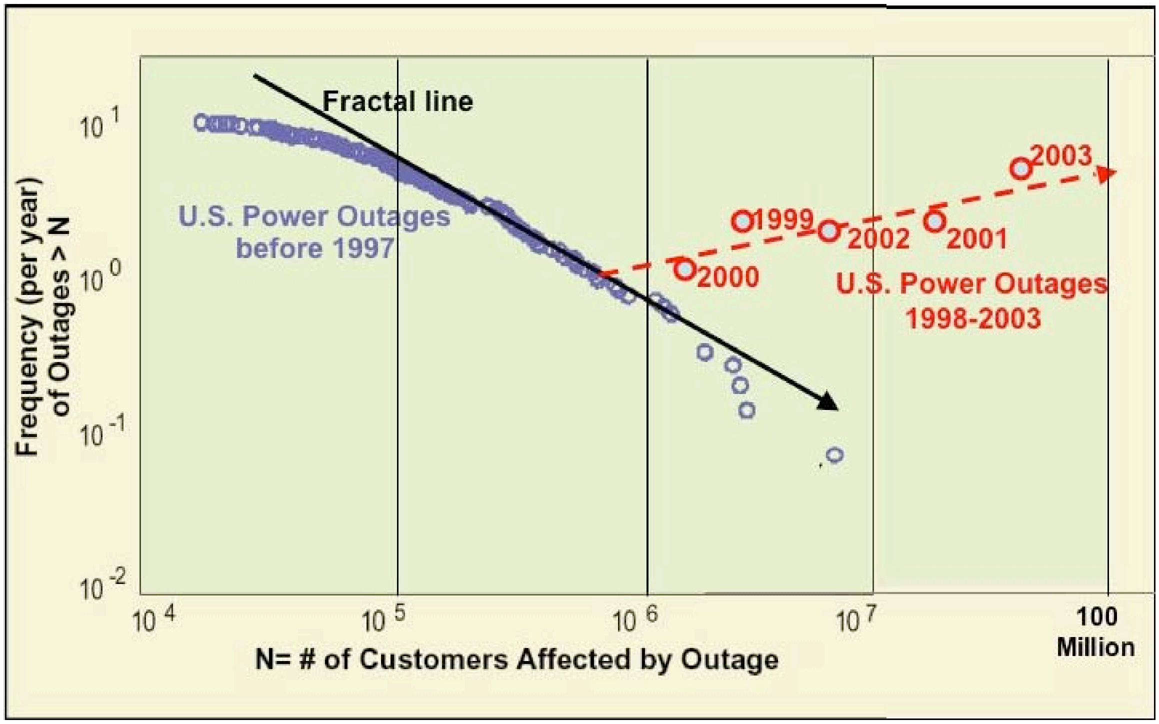


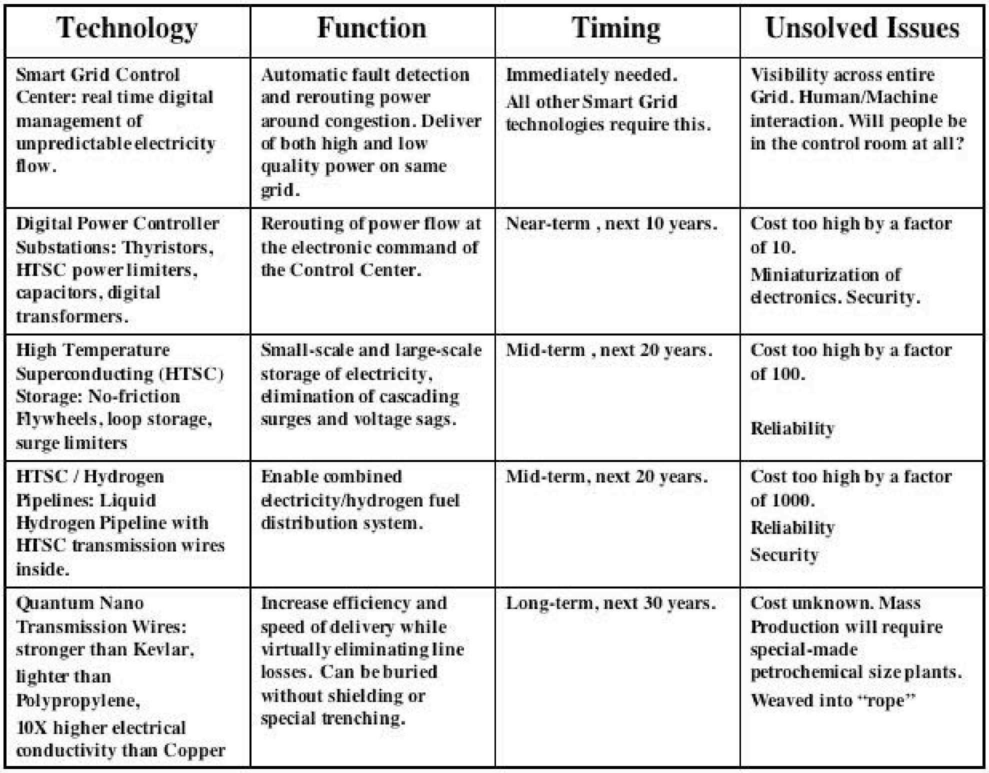
Figure 1. The U. S. electric grid has become more unstable since 1998, with more failures that affect large populations of customers than extrapolating of the previous 50 years would predict (Background plot from Amin, IEEE Computer Applications in Power, 2001).

A computerized control capability could be used to model and better understand the electric grid, yet none exists to date that can visualize the entire North American grid. Such computer assistance is particularly needed because the grid is exhibiting more and more behavior characteristic of chaotic systems. Since electricity on the grid is free flowing, it moves as power pulses at nearly the speed of light (10^{10} cm per second). However, in reality, electrons flow back and forth between the power plants and the consumers at speeds slower than the flow of these power pulses. The electrons can "only" move along the copper and aluminum wires and transformers of the transmission grid at velocities between 10^7 and 10^8 cm per second.[3] This disparity produces the "non-linear" behavior of the system affecting the flow of electricity in unpredictable ways.

In addition to computer software more akin to the internet or air traffic control systems, new hardware is needed to provide buffers to the cascades of failures that are caused by congestion and disruptions of the flow of electricity—failures that propagate across the grid. Power switches that combine thyristors (the electrical equivalent of transistors which direct information in the computer) to redirect flow with capacitors to provide buffering storage would give the grid operator the option of redirecting electricity around obstacles and disturbances at the speeds needed to forestall failures. Currently flow can only be redirected through the use of mechanical circuit breakers at speeds adequate for most present, but not future, conditions. There are a few of these experimental devices installed in the United States but their cost is currently too great for large-scale usage.

On top of such electronic aid, distributed storage and generation hardware such as High Temperature Superconductivity (HTSC) storage must be added to the transmission grid to provide the capability to smooth out intermittent and unpredictable flow from large-scale wind and solar farms. HTSC's have no resistance to electricity flow at supercritical temperatures, but if heated up, for example, by an electricity spike, HTCS become resistive and limit the propagation of the power surge. Surges and sags in power could then be dealt with in fractions of a second without shutting down the whole system. This technology is currently too expensive (see table 1), as well as being improperly incentivized to gain widespread use today. For example, regulators do not allow utilities to recover the costs of purchasing such equipment through consumer electricity rates. Yet these large-scale storage systems must be in place before we can decentralize the grid to accommodate significant amounts of smaller distributed generation (DG) and distributed storage (DS) capabilities. These kinds of new grid hardware, e.g., HTSC, thyristors, and capacitors—commonly grouped into the term "power controllers"—together with DG and DS, will make the overall grid network more efficient and stable by flattening out peak-demand spikes and load variability.

These power controllers would also allow operators to charge a higher fee for high quality power while no additional fees would be charged to users that don't need completely stable power. The ability, provided by power controllers, to switch the flow of electrons is required for this type of dual power system, in which higher quality, more reliable power can be delivered at an added cost only to those consumers that need it, while lower-quality, less reliable, less expensive power could be delivered to the rest of us. The home is little affected by momentary brownouts, but such brownouts wreck a semiconductor assembly line. Added revenue sources, such as from a dual system, are needed to attract the private capital that is needed to upgrade and maintain the long-distance transmission system so that it can accommodate vast new wind and solar "farms." Presently, we all get the same high-quality, expensive power (99.999% of the time it is within a strict range of voltage and frequency, called "5 9's" in the power business).



Technology	Function	Timing	Unsolved Issues
Smart Grid Control Center: real time digital management of unpredictable electricity flow.	Automatic fault detection and rerouting power around congestion. Deliver of both high and low quality power on same grid.	Immediately needed. All other Smart Grid technologies require this.	Visibility across entire Grid. Human/Machine interaction. Will people be in the control room at all?
Digital Power Controller Substations: Thyristors, HTSC power limiters, capacitors, digital transformers.	Rerouting of power flow at the electronic command of the Control Center.	Near-term , next 10 years.	Cost too high by a factor of 10. Miniaturization of electronics. Security.
High Temperature Superconducting (HTSC) Storage: No-friction Flywheels, loop storage, surge limiters	Small-scale and large-scale storage of electricity, elimination of cascading surges and voltage sags.	Mid-term , next 20 years.	Cost too high by a factor of 100. Reliability
HTSC / Hydrogen Pipelines: Liquid Hydrogen Pipeline with HTSC transmission wires inside.	Enable combined electricity/hydrogen fuel distribution system.	Mid-term, next 20 years.	Cost too high by a factor of 1000. Reliability Security
Quantum Nano Transmission Wires: stronger than Kevlar, lighter than Polypropylene, 10X higher electrical conductivity than Copper	Increase efficiency and speed of delivery while virtually eliminating line losses. Can be buried without shielding or special trenching.	Long-term, next 30 years.	Cost unknown. Mass Production will require special-made petrochemical size plants. Weaved into "rope"

Table 1. Major new components of the new distributed Storage-Generation Smart Grid of the future.

20-30 Year-out Technology Needs

There is great promise that high temperature superconductivity and nano-meter scale technologies will deliver several breakthroughs that could revolutionize the grid 20-30 years out. The high temperature superconductor/liquid hydrogen (HTS/LH_2) super energy highway newly proposed by EPRI and DOE might provide the clean and green energy in both electrical and chemical forms to power urban transportation and electricity needs simultaneously. This "Super Grid" would use a high-capacity, superconducting power transmission cable cooled within a liquid hydrogen pipeline, with the hydrogen used in fuel cell vehicles and generators. The Super Grid would accelerate the deployment of HTSC technology by relaxing the stringent requirements and removing a major cause of failure of existing superconductors. At present HTSC costs are excessive because of the insulation requirements to keep HTSC devices cold. Placing the HTSC inside liquid hydrogen pipelines would eliminate the need to insulate them. In such a system, electricity and hydrogen provide a joint pathway for us to become progressively less dependent on fossil fuels, reducing GHG and pollutant emissions, and increasing the capability of the grid to accept large contributions of renewable energy sources.

Nano-scale transmission wires, called quantum wires (QW), might revolutionize the grid even further. QW has electrical conductivity that is higher than copper at one sixth the weight, and twice the strength of steel. A grid made up of such transmission wires would have no line losses or weather dependencies, eliminating the need for massive emergency generation capacity, and the grid could be buried without any special handling. The transmission wires of the grid, if made from such QW would be virtually immune to weather-induced outages, especially if laid underground. QW will perhaps be spun into polypropylene-like rope that is non-corrosive and can be buried "forever" with no fear of corrosion and no need for shielding of any kind. However, massive factories will surely be required to "weave" the QW in the quantities needed by the grid. There are more than 700,000 miles of transmission lines in the United States alone at this time.

Barriers to Success

A smarter grid is required to provide efficient, clean, plentiful, safe and secure energy to power continued economic development with lessened environmental impact. It could even be a web-enabled, digitally controlled, intelligent delivery system for both power and transportation services.

How we get there from here is a much harder question. Currently, there are no incentives for fixing the grid beyond short-term patches like laying additional transmission wires around congestion. That strategy is much like urban highway construction – the more lanes a city provides, the more traffic the road attracts, producing more congestion, requiring more lanes, etc.

I believe we must create several national test beds to experiment with how to deploy new smart grid technologies on a large scale and in an integrated way. Such test beds would combine promising technologies (see Table1) in various configurations and experiment with how the system is improved through their use. Designing a smart grid is difficult to do if individual technologies are deployed in isolation. Such test beds MUST already be in operation within 10 years if we are to meet the power needs of the continent 20-30 years out. The grid cannot be experimented with "live." We must be certain that the grid is capable of handling each new technology BEFORE it is deployed. It is not an option to connect new gadgets directly to the grid, and accidentally cause massive, cascading blackouts. The problem with creating such national test beds is that the electricity industry has among the lowest R&D expenditures of all companies (Technology review, 2003). The federal government must recognize the electric grid as vital to our prosperity and national security. A DARPA-like organization is required. DARPA (Defense Advanced Research Projects Agency) funded, among other developments, the Internet and super computers. Such an effort, dedicated to modernization of the electricity grid, is needed within the U.S. Department of Energy.

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[1] U.S. DOE. 2003. *National Electric Delivery Technologies Vision and Roadmap*. November. 2003. Available for download at: http://www.energetics.com/electric.html

[2] A relationship between two variables is defined as being "fractal" if it is linear when examined in exponential or "log-log" space…that is, the same across many scales.

[3] Termed the Fermi velocity.

Present and Future Electricity Storage for Intermittent Renewables

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Intermittent Renewables in the Context of Stabilizing Atmospheric CO_2

Stabilizing future atmospheric carbon dioxide (CO_2) levels at less than a doubling of pre-industrial levels will be a Herculean task, requiring a continuous flow of new carbon-free power 2-3 times greater than today's energy supply to sustain economic development for a global population approaching 10 billion by the mid 21st Century. The sun and wind are the two largest sustainable sources of carbon-free power, but in spite of dramatic cost declines for solar and wind technologies, for the most part they remain more costly today than electric generation from fossil fuels, especially in the case of photovoltaics (solar cells). The costs of solar and wind power are partially offset by their potential benefits as distributed electricity generation sources. However, even if future development reduces their cost substantially, widespread deployment of solar and wind power in the future will face the fundamental difficulty that they are intermittent, requiring demand flexibility, backup power sources, and very likely enough electricity storage for days to perhaps a week.

Energy Storage Technologies

Electricity is not usually stored *per se*. Energy storage technologies instead convert electricity to other energy forms (gravitational, pneumatic, kinetic, chemical), with a characteristic turnaround efficiency usually driven by the simplicity or complexity of conversion and reconversion between electricity and the stored energy form. For example, it can be 90-95% efficient to convert electricity to kinetic energy and back again by speeding up or slowing down a spinning flywheel. Storing electricity by compressing and later re-expanding air is usually less efficient (75%), since rapid compression heats up a gas, increasing its pressure, making further compression difficult. The electric energy lost in energy storage drives up the overall cost of generating reliable electricity from wind or solar power. Another cost of energy storage is the capital investment required for the energy storage system. These costs are driven by the weight of material or volume of containment vessels needed to store a given amount of energy, termed energy density (kWh/kg or kWh/liter), again characteristic of each energy storage form.

Pumped hydroelectric and compressed air energy storage (CAES) are currently economic for utilities when relying on natural geologic formations and the cheapest, most abundant substances (i.e. elevated water and compressed air). In these situations the cost of energy storage capacity can be very low (<\$5/kWh[1]) Unfortunately the scale and location-specific nature of energy storage in natural formations is likely to render it of limited benefit to small scale distributed renewables. Available pumped hydro and CAES capacities could prove small in relation to the overall amount of future global renewable electricity—and attendant storage requirements—necessary for massive reductions in greenhouse gases. If energy storage in existing natural formations turns out to be insufficient, then man-made energy storage systems will be needed to support massive deployment of intermittent renewables.

Among man-made energy storage systems, the most well-known is the battery, used today to store electricity from solar photovoltaic systems located where the grid is not available to back up solar power. Batteries are electrochemical energy storage devices which can be relatively efficient (~70-80%) if charged and discharged at moderate rates. Batteries are very modular and are therefore technically well-suited to use with small scale distributed renewables. The chief difficulty of battery technology is short life (~1000's of cycles equivalent to 3-5 years in daily use) which, given the their capital cost ($100-200/kWh of storage capacity), can make storing electricity in batteries at least as expensive as generating electricity. Additionally, in the context of deep greenhouse gas reductions, the sheer scale of raw material needed for batteries (billions of tonnes) would likely outstrip the known reserves of common battery materials (lead, nickel, cadmium), further increasing battery cost. Such huge quantities of battery materials might also need to be recycled nearly indefinitely to minimize disposal issues and environmental impacts.

An emerging alternative to batteries is the high-speed flywheel. Since there are no chemical reactions to reverse and little friction (flywheels are typically levitated by magnets in a vacuum chamber), flywheels have the technical strengths of high efficiency (~95%), high power, and long life. Dubbed "electromechanical batteries" by a chief early proponent, Richard Post, flywheels store kinetic energy in a cylindrical or ringed mass, spinning at very high speeds (~10,000-20,000 rpm), for high energy density (0.1-1 kWh/liter). Key issues for flywheels are safety and cost. Addressing the safety of deploying millions of flywheels would likely require underground use and/or stringent containment designed to withstand high-speed (~ 1000 miles per hour) fragments from a broken flywheel. This will likely place a lower limit on flywheel system capital costs. Flywheel capital costs are currently projected to be $200-500 per kWh of storage capacity at scales of 100-300 kWh of storage capacity, a size larger than appropriate for a single residence, but perhaps better scaled to a neighborhood grid or substation. The performance of flywheels depends critically on the materials of its construction with a significant premium on strength-to-weight ratio. Performance has improved dramatically over the last two decades with progress in ultra-high strength composite materials. If future developments reduce the cost of ultra-high strength materials, flywheels will be substantially more attractive. Currently, flywheels are just beginning commercialization for high-value uninterruptible power applications. If they become economic in a renewables context, flywheels, are likely to be best employed for routinely (i.e. daily) storing small amounts of energy delivered at high power for short times (1-2 hours), or perhaps to smooth out peaks in power demand into and out of a much larger battery storage system (improving battery life).

Electrolytic Hydrogen: A Future Technology for Energy Storage

In the future, predominantly solar or wind power systems will likely require energy storage for days to approximately a week, with or without connections to the electric grid. If so, conversion of electricity to chemical energy is potentially attractive, since chemicals are inexpensive to store and turnaround efficiency is less critical for storage periods of a week or more. The most attractive chemical for this process is likely to be hydrogen (H_2) generated locally by electrolysis of water using intermittent excess solar or wind power. Later, when combined with air or oxygen (O_2) in engines or fuel cells, H_2 can regenerate electricity on demand. Although H_2 electricity storage is less energy efficient (40-50%) than compressed air storage, H_2 has *far* lower costs of storage capacity, since H_2 is a chemical fuel and air is not. For example, a 250-liter pressure vessel designed to store 10-20 kWh of compressed air could store enough H_2 to provide 150-300 kWh of electricity, reducing the cost of storage capacity by more than a factor of 10. H_2 energy storage is therefore economically best suited to situations where the total amount of energy stored is more valuable than efficiency. This should be the case for electricity stored longer than 1-2 days. H_2 may also be stored cheaply without high pressure as a very low temperature (-453 ^{o}F) liquid (LH_2) or by absorption in powders of abundant metals (e.g. iron, titanium, aluminum, and sodium) that release H_2 upon moderate heating (<200 ^{o}F).

Energy Storage within a Hydrogen Transportation Fuel Infrastructure

A predominantly renewable electricity supply could be combined synergistically with a future carbon-free *electrolytic* H_2 transportation sector. Co-production of electricity and H_2 fuel would enable massive deployment of intermittent electric generation by making efficient use of otherwise almost unavoidable excess generation during some time periods. The reliability of solar and wind power could also be improved through intentional "oversizing" of generation capacity relative to demand, since the additional excess electricity could produce H_2 fuel. The energy stored in the H_2 infrastructure and/or onboard H_2 vehicles would be large enough to buffer H_2 demand on the time scale of days. When wind or sunshine were low, higher H_2 prices would temporarily reduce H_2 demand from vehicles. Later, when solar and wind electricity supplies returned to higher levels, accumulated demand for H_2 fuel could be easily met and H_2 prices could drop. Furthermore, if travel patterns and/or vehicle use were flexible over short periods (i.e. days), then the transportation sector could also vary transportation use in response to H_2 supply and cost levels.

Further integration of the electricity and H_2 transportation sectors could, in principle, include the very large latent energy storage capacity of H_2 vehicles as back-up power sources or even routine energy storage. A future H_2 hybrid-electric or fuel cell automobile with 5-10 kg of H_2 onboard (energy equivalent to 5-10 gallons of gasoline) could provide 75-150 kWh of electricity, enough to power a typical home for up to a week. The amount and efficiency of back-up power available from a H_2 automobile would actually *grow* with consumer demands for greater size, power, and driving range. This would turn what is otherwise an engineering challenge (designing a cost-competitive H_2 vehicle with range and performance comparable to or better than conventional gasoline vehicles), into a value-added benefit.

Conclusions/Recommendations

It appears that in the short term (through approximately 2020), intermittent renewables will either depend upon the grid for back-up power or use batteries for energy storage. Flywheels could potentially store energy on a daily basis, especially if flywheel materials improve. In the farther future (perhaps 2040), much larger greenhouse gas emission reductions will become necessary, and with it the need for greater use of intermittent renewables and significant electricity storage. For very large amounts of electricity storage, the availability of geologic formations for compressed air energy storage (CAES) and raw materials for batteries, as well as the need for recycling them, could become limiting factors. If the cost of high strength materials, underground installation, and/or safe containment of accidents limit the maximum deployment of flywheels as well, then electrolysis to produce hydrogen for routine storage for vast amounts of energy worldwide becomes attractive.

The storage needs of a predominantly (intermittent) renewable electricity supply may ultimately be best met in the future by increasing levels of integration with a hydrogen (H_2) fueled transportation sector. In addition to reducing greenhouse gases from transportation, this long-term option could have unique energy security, electricity reliability, and market-efficiency benefits which may be foregone if H_2 production, storage, and vehicle technologies are not developed and deployed in coordination with intermittent renewables.

It is therefore important that hydrogen research and development efforts focus on technologies enabling efficient integration of future carbon-free transportation *and* electricity generation. Examples would include much higher-efficiency electrolysis and fuel cells, and reversible systems that can produce H_2 from electricity as well as electricity using H_2, potentially in homes or on vehicles. In addition, policy attention should be paid to future regulations covering distributed electricity generation, hydrogen vehicles, fuel stations, and electricity systems for buildings to insure economic and efficient interaction between all these critical components of a future energy system powered predominantly by well-integrated intermittent renewables.

---

[1] There can sometimes be confusion between the capital cost of electricity storage *capacity* (given throughout this paper in \$/kWh of storage *capacity*) and the cost of electric power delivered from storage, usually given in \$/kWh or cents/kWh). Generally, the cost of storage capacity ranges from ~ \$5-500 \$/kWh, and is amortized over many (i.e. thousands) charge-discharge cycles to determine its contribution to the price of electricity delivered from storage.

policy

Opportunities in Industry Presentations

technology

PEW CENTER ON Global CLIMATE CHANGE

National Commission on Energy Policy

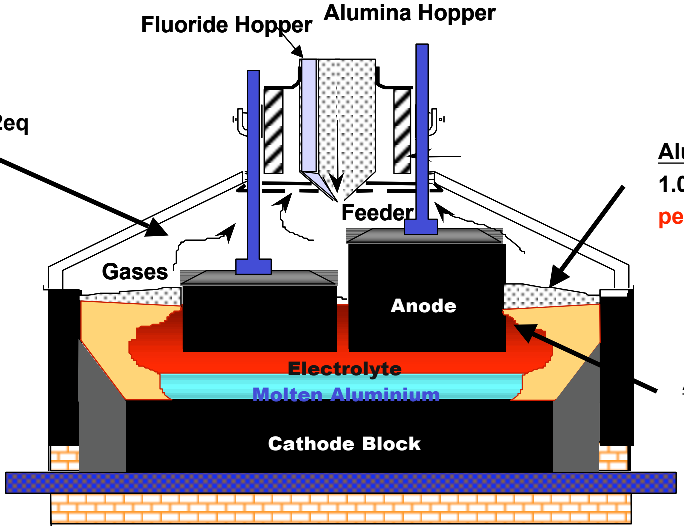
De-Coupling Business Growth from Carbon Emissions - Opportunities in Industry

Pew Center on Global Climate Change/
National Commission on Energy Policy
"10-50 Workshop"

Alcoa's "10" year plan

- Alcoa has committed to reducing its direct GHG emissions by 25% from a 1990 base by 2010. Alcoa has achieved the 25% reduction as of 2003 and is now working to maintain the reduction as the company expands by up to 40% by 2010. (No additional GHG emissions)
- We will expand using low-carbon technologies and sources of electric power that are as efficient as practicable.
- There are technology limitations associated with our processes as well as socioeconomic/political limitations associated with power availability, but these limitations should not impact our plans through 2010.
- We will continue to emphasize efficiency and sustainability in our product designs and applications.

Hall - Heroult Process
Center Point Break Prebake Anode Cell



PFC Generation
0.3 - 10.8 t of CO2eq

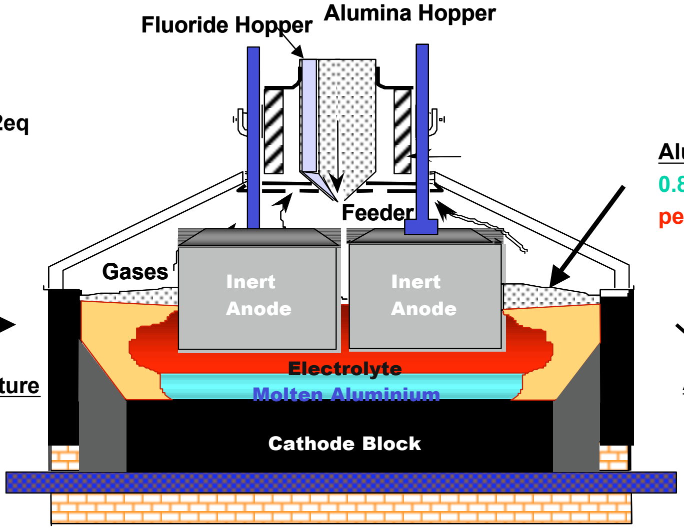
Alumina Production
1.0 - 1.5 t of CO2eq
per ton of aluminum

Anode Carbon
1.5-2.0 t of CO2eq

Fabrication
0.6 - 1.3 t of CO2eq

Total
3.9 - 15.6 t of CO2eq

Hall - Heroult Process
Center Point Inert Anode Cell



~~**PFC Generation**~~
~~0.3 - 10.8 t of CO2eq~~

Alumina Production
0.8 - 1.5 t of CO2eq
per ton of aluminum

Inert Anode Manufacture
0.2 - 0.3 t of CO2eq

~~**Anode Carbon**~~
~~1.5- 2.0 t of CO2eq~~

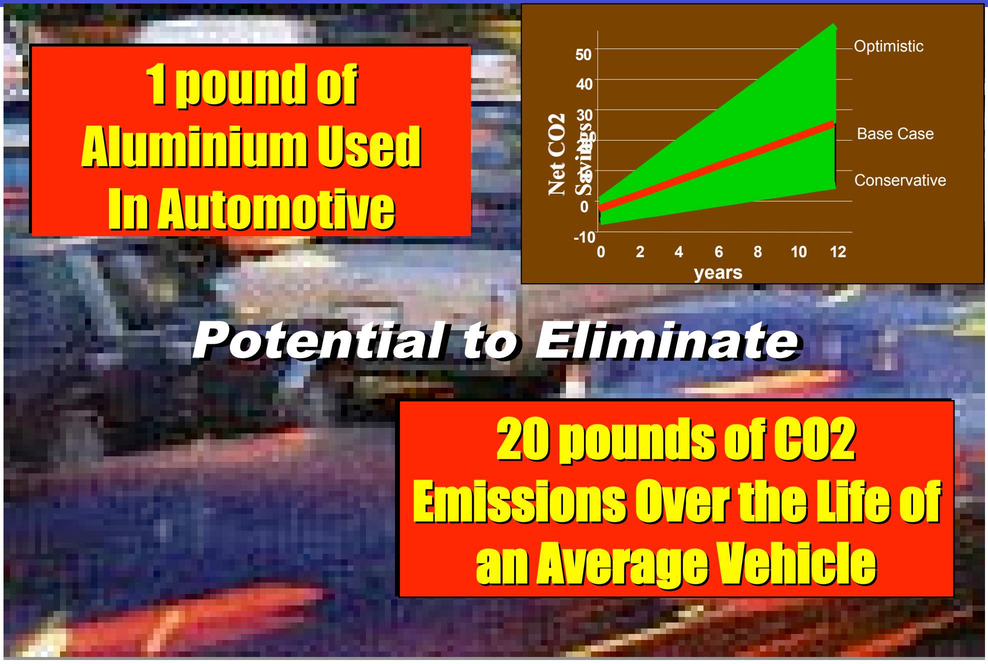
Fabrication
0.6 - 1.3 t of CO2eq

Total
1.6- 3.1 t of CO2eq

Alcoa’s Business in 2050

- Alcoa will be a low carbon emitter with the use of inert anodes and highly efficient processes that will reduce GHG from our processes by 50%.
- Alcoa will source electric power from highly efficient providers that manage GHG emissions well.
- Alcoa products will be designed to minimize GHG emissions by our customers, and all GHGs associated with aluminum production, fabrication and recycling can be completely offset by product use.
- Alcoa, through products and processes, will be a net reducer of GHGs in society.

Life Cycle Modeling



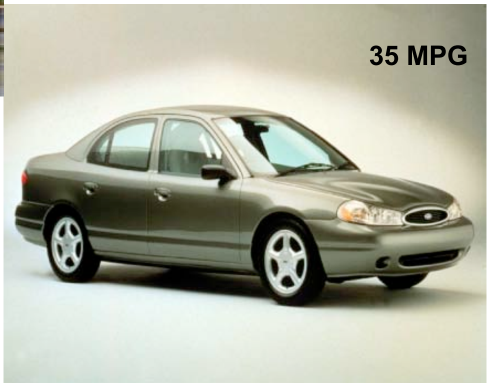
1 pound of Aluminium Used In Automotive

Potential to Eliminate

20 pounds of CO2 Emissions Over the Life of an Average Vehicle

Life Cycle Data - Improved Vehicle Fuel Economy

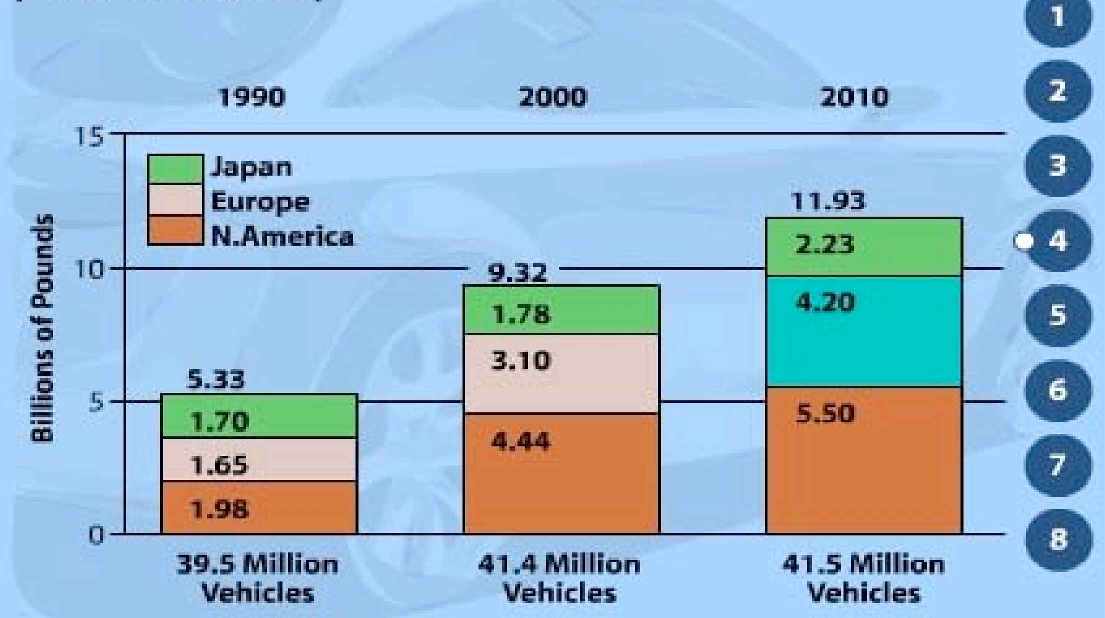
Improved fuel economy 30%



Weight saving 40 %

Executive Summary & Assumptions For The Future

Global Light Vehicle Aluminum Content (Billions of Pounds)



Source: Ducker Research Company, Inc.

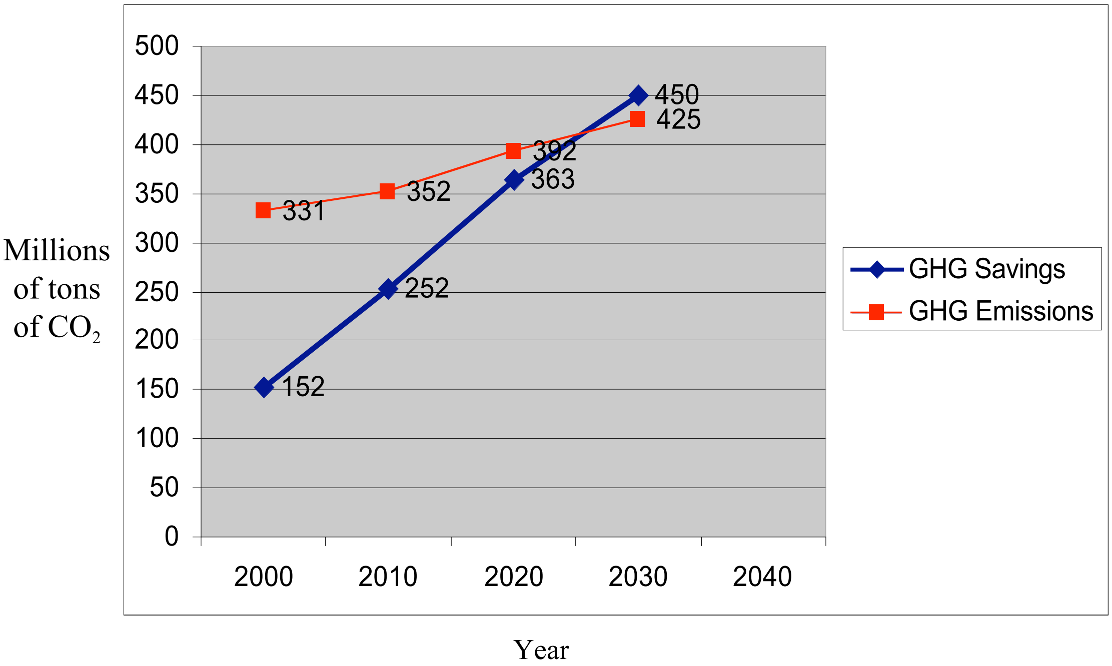
ENVIRONMENTAL – GHG EMISSIONS

Year		1950	1990	2000	2002	2010	2015	202
			Units 1000 Metric tons unless noted					
Metal balance								
Demand		2,741	35,308	49,912	50,400	61,666	70,242	80,267
Scrap return		1,096	17,306	25,103	25,463	32,055	36,550	43,053
Primary consumed		1,645	18,001	24,810	24,937	29,611	33,692	37,215
Ratio All Scrap/Primary	ratio	0.40	0.49	0.50	0.51	0.52	0.52	0.54
Primary Consumed/ Needed								
pre 2004 need		1,645	18,001	24,810	24,810	24,810	24,810	24,810
post 2004 need						4,802	8,882	12,405
GHG Intensity - Primary								
pre 2004 capacity	MT CO2e/	13	13	13	13	12	12	12
post 2004 capacity	MT AL					6	6	6
			Assumed Improvement Rate		0.995	0.995	0.995	0.995
Production CO2e Calculations								
New Capacity CO2e						28,809	53,293	74,429
Total primary CO2e		20,889	228,562	315,009	313,434	329,923	346,954	360,822
Predicted Scrap CO2e		1,096	17,306	25,103	25,463	32,055	36,550	43,053
Total Production CO2e		21,985	245,869	340,112	338,897	361,979	383,504	403,874

ENVIRONMENTAL – GHG SAVINGS

Year		1950	1990	2000	2002	2010	2015	202
GHG Intensity - Ingot & Products								
CO2 per Al processed	MT CO2e/	8.0	7.0	6.8	6.7	5.9	5.5	5.0
CO2 per Net Shipments	MT AL	11.1	9.6	9.5	9.3	8.1	7.6	7.0
Potential Transport Savings								
Auto & LT shipments		345	5,293	8,322	8,516	11,836	14,539	17,860
% increase - decade				57%		40%		40%
Savings/tonne auto	MT CO2e/ MT Auto Al	20	20	20	20	20	20	20
Heavy Transport - Shipments		81	915	1,522	921	1,290	1,592	1,965
Savings/tonne Rail/Truck/Bus		40	40	40	40	40	40	40
Amortised credit for transport								
Savings/tonne/year (12 year life)		1.67	1.67	1.67	1.67	1.67	1.67	1.67
Total credit (Auto)			-92,038	-139,650	-150,974	-205,566	-249,035	-305,913
Savings/tonne/year (25 year life)		1.6	1.6	1.6	1.6	1.6	1.6	1.6
Total credit (rail etc)	MT CO2e		-26,274	-38,811	-40,612	-46,334	-51,063	-57,691
Total Saving Transport	MT CO2e		-118,312	-178,460	-191,586	-251,900	-300,098	-363,604
Total Al Production CO2e	MT CO2e		245,869	340,112	338,897	361,979	383,504	403,874
Net total GH (Production -	**Transport)**		127,557	161,652	147,311	110,079	83,406	40,270

Aluminum Industry GHG Budget



Competitiveness

- Alcoa sees GHG reductions as a process improvement strategy. Given enough flexibility, we see our GHG management program as a positive contributor to Alcoa's sustainability (financial, environmental, social progress)
- Overall, aluminum and Alcoa will be more competitive in <u>most</u> of our markets as low-GHG pathways are adopted. There must be flexibility to avoid major disruptions, such as efficient emissions trading opportunities since there will be some losses of markets and businesses over time.
- The uncertainties associated with the lack of worldwide constraints, or at least an articulated strategy for worldwide constraints can impact regional competitiveness

Policy Signals for Business Action

- Uniform measurement and reporting standards worldwide.
- Efficient emission trading programs that are market based and worldwide.
- A process to identify and provide some credit or at least recognition for GHG reductions that result form material use and product design to companies such as Alcoa.
- Mechanisms to reward developing countries for the use of efficient processes and low GHG emitting approaches to satisfying the needs of their societies.
- Government engagement in approaches such as “reverse auctions” to signal support for action on GHG reduction.

Pew Center/NCEP "10-50" Workshop

Coupling Business Growth

with lower carbon emissions

Chris Mottershead

BP's business towards 2050

- BP's role is to provide the energy, that fuels economic and social progress, by meeting the growing demand for affordable energy, whilst respecting the broader needs of communities and the environment.
- Gas will be fastest growing fuel in the next 25 years because of increasing demand for clean and low cost power.
- Liquid hydrocarbons will continue to dominate transport fuels for at least the next two decades – increasing efficiency through dieselisation, direct injection and hybridisation.
- Resource productivity and energy efficiency is simply good business
- BP believes it is necessary to stabilise atmospheric concentrations of GHG in the range 500-550ppm – this can only be met through a portfolio of new technologies, markets and businesses. BP will invest in those areas which it believes will be material, profitable and where it has a sustainable competitive advantage; for example solar pv, hydrogen and carbon capture & storage.

BP's "10 year" plan

- Emission reductions
  - improve the energy efficiency of our operations – within the first three years this led to a reduction of 17Mt of GHGs, and the creation of $650M of additional value.
  - however – the growing demand for cleaner fuels will mean an increase in total BP emissions, e.g. low sulphur fuels and LNG.
  - BP is committed to holding net emissions flat, by demonstrating the net carbon benefit from our growth - based on whole life cycle analysis of product emissions.

- Business growth
  - analysis leads us to believe that it is necessary to stabilise atmospheric concentrations of GHGs in the range 500-550ppm, and that:
    - the cost of doing this is small, and the economic benefits positive.
    - emissions from the current fossil fuel industry could be similar in 2050 as they are today, assuming a continued shift from coal to gas.
    - there is a need to create a zero emissions primary energy sector by 2050 similar in size to the existing industry – this can be achieved by portfolio of solutions (seven '1Gtc wedges').
  - three areas of public policy need to be addressed during the next decade if stabilisation is to be achieved:
    - Technology development: a limited number of material and potentially profitable technologies need to be developed – materiality test is 1Gtc/year avoided in 2050.
    - Market development: continued promotion of market engagement processes, such as cap and trade systems, product labelling and public education.
    - Business development: increasingly countries and businesses will come under economic pressure from competitors – with more attractive lower carbon products and services, or from more efficient economies/operations: key will be the economic development policies used to sustain and retain competitively advantage businesses.

Competitiveness

- BP believes it is prudent and necessary to take a path towards a lower carbon future.
- As a fossil fuel company its future is dependent upon creating solutions that allow the continued growth in energy demand, while respecting the environmental limits imposed by nature.
- Ultimately responding to the challenge will have positive benefits for communities and businesses that seek out opportunities for growth and efficiency.
- While some countries and businesses have started to recognise the economic benefit from having innovative lower carbon products and markets, e.g. Carbon Trust in UK, BP believes that it needs to move beyond this, and that there is real competitive advantage to be gained from making a significant contribution to shaping the future agenda for society and business.
- Ultimately competitiveness will be achieved by having open and transparent energy markets, supported by an integrated portfolio of public policies, which are consistent with other local, regional and national policies to support lower carbon:

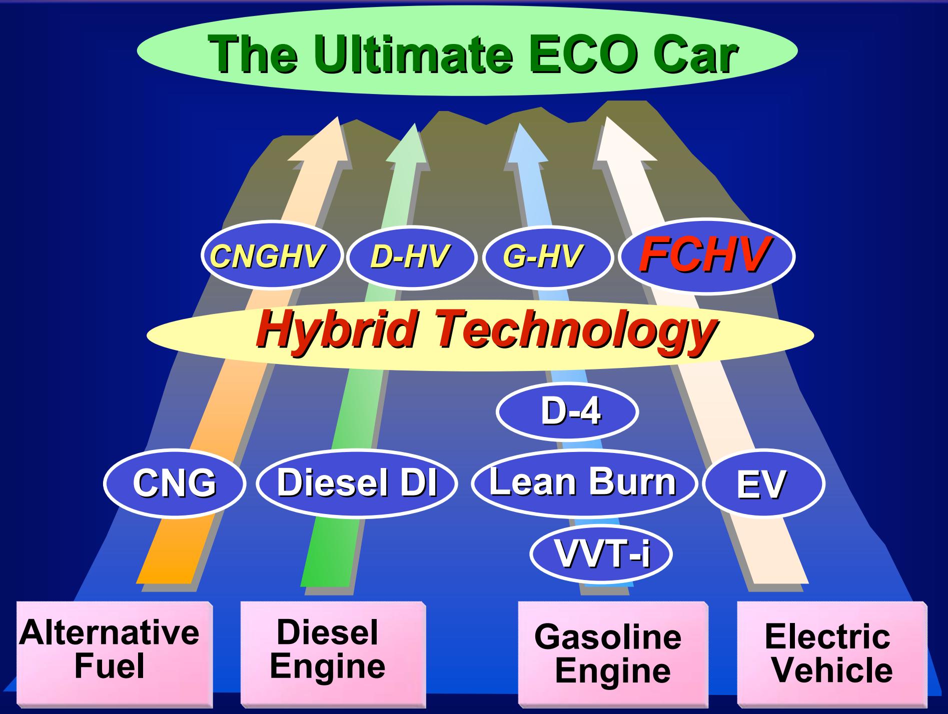
Technology development
Market development
Business development

Pew Center/NCEP “10-50” Workshop
Washington, D.C.

De-Coupling Business Growth from Carbon Emissions

Robert Wimmer
Environmental Research Manager
Toyota Motor North America
March 25-26, 2004

TOYOTA's Business in 2050



The Ultimate ECO Car

CNGHV
D-HV
G-HV
FCHV

Hybrid Technology

D-4
CNG
Diesel DI
Lean Burn
EV
VVT-i

Alternative Fuel
Diesel Engine
Gasoline Engine
Electric Vehicle

Toyota's "10" Plan

Prius

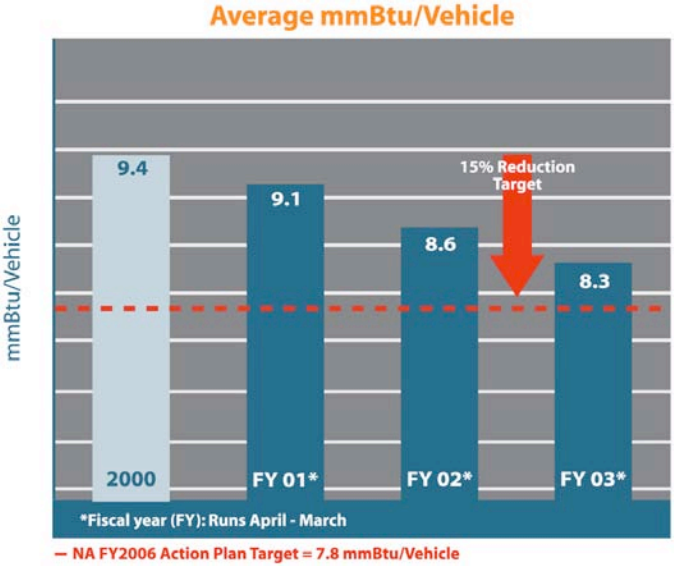
FCHV

RX 400h

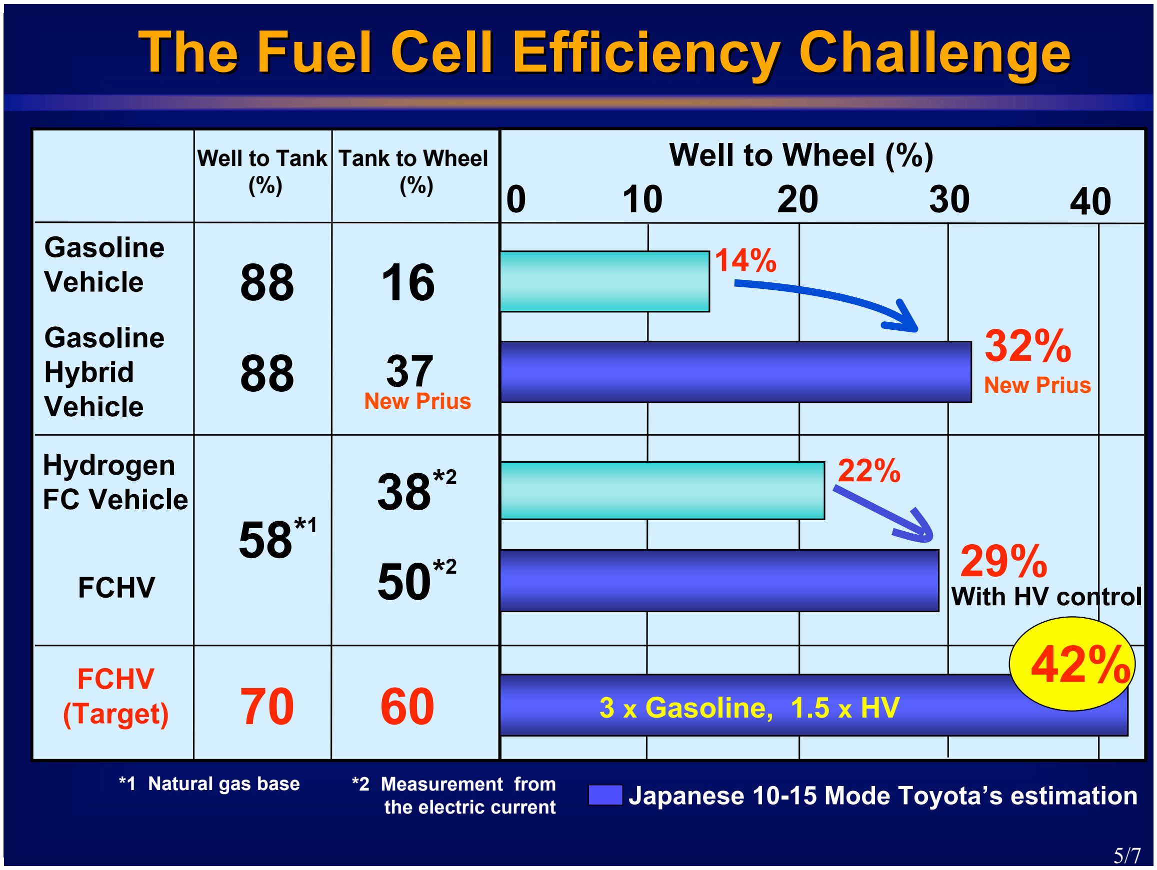
<u>In the near term, Toyota is</u>

- Increasing production of Prius
- Hybridizing additional models
- Developing hydrogen-fueled fuel cell powered vehicles

Energy Reduction in Manufacturing



Toyota is reducing the energy consumed in vehicle manufacturing by 15%



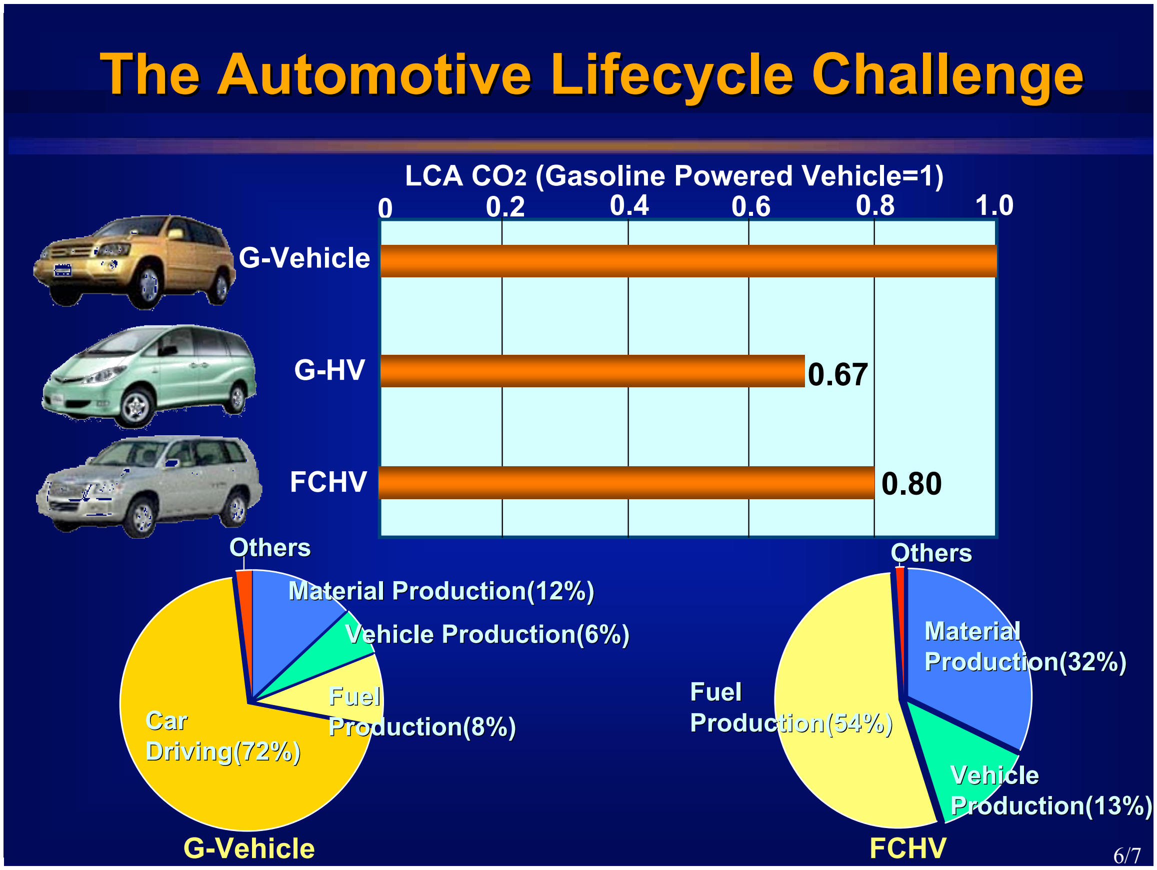
The Fuel Cell Efficiency Challenge

	Well to Tank (%)	Tank to Wheel (%)	Well to Wheel (%)
Gasoline Vehicle	88	16	14%
Gasoline Hybrid Vehicle	88	37 New Prius	32% New Prius
Hydrogen FC Vehicle	58[*1]	38[*2]	22%
FCHV		50[*2]	29% With HV control
FCHV (Target)	70	60	42% 3 x Gasoline, 1.5 x HV

[*1] Natural gas base

[*2] Measurement from the electric current

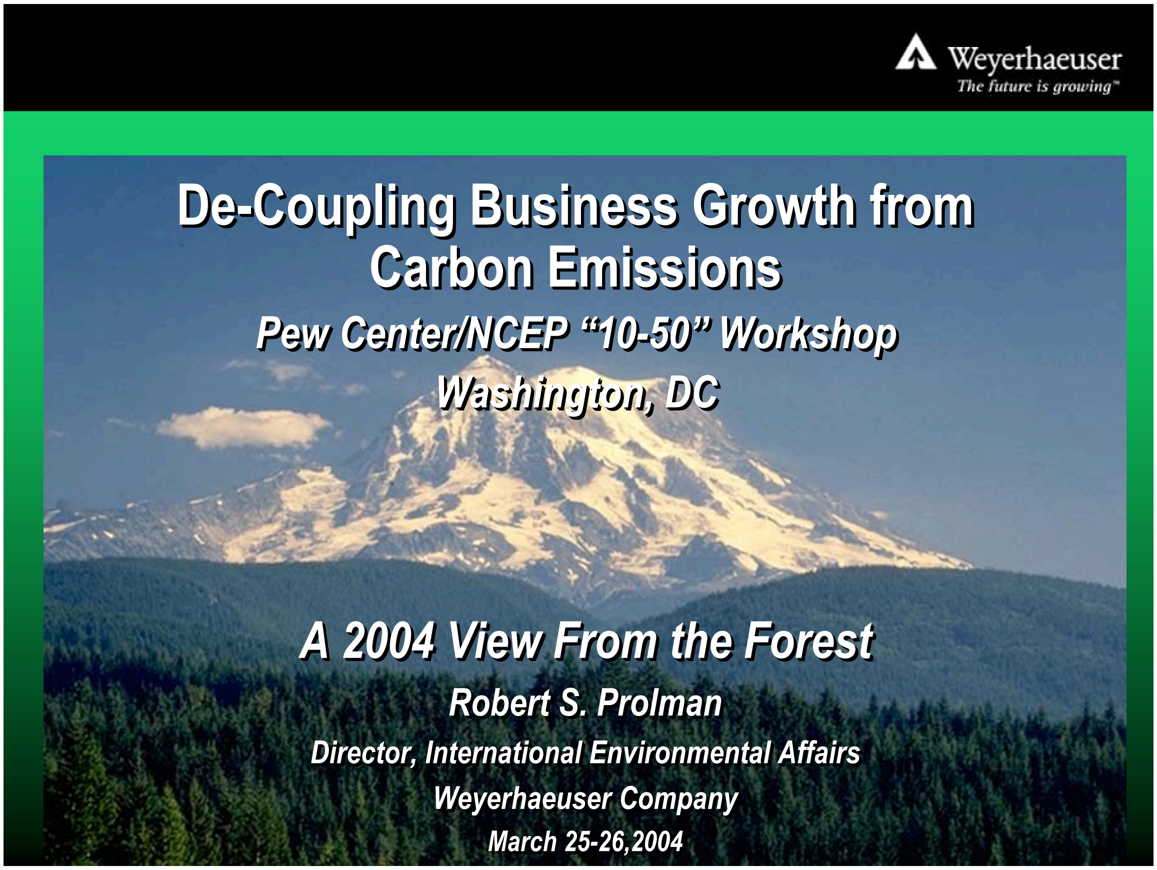
▇ Japanese 10-15 Mode Toyota's estimation



The Automotive Lifecycle Challenge

Policy Signals for Business Action

- Near-term promotion of hybrids, via tax credits, will accelerate technology introduction (don’t procrastinate)
- Standardize National & International regulations for emissions and fuels
  - Costly to develop unique systems for every market (Europe, Japan, US, and CA/NY/NJ)
- Policies that promote the development of low cost/low GHG H_2, CO_2 sequestration and H_2 infrastructure



Weyerhaeuser
The future is growing™

De-Coupling Business Growth from Carbon Emissions

Pew Center/NCEP “10-50” Workshop
Washington, DC

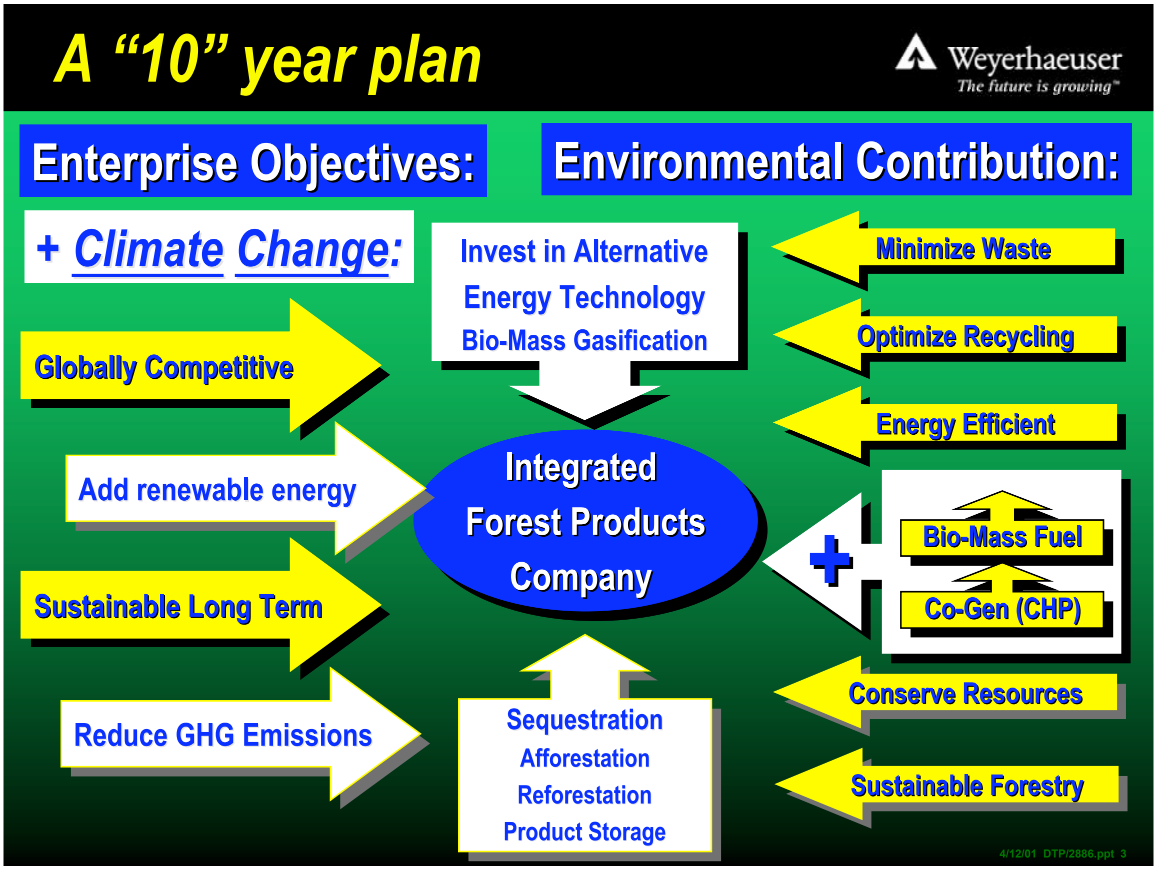
A 2004 View From the Forest

Robert S. Prolman
Director, International Environmental Affairs
Weyerhaeuser Company
March 25-26,2004

Our business in 2050:

Weyerhaeuser
The future is growing™

- A global leader in the production of renewable building products
- An industry leader in the use of GHG-neutral biomass energy technology
- International sustainable manager and developer of forests that sequester millions of tons of atmospheric carbon



A "10" year plan

Weyerhaeuser
The future is growing™

Enterprise Objectives:

Environmental Contribution:

+ *Climate Change:*

Globally Competitive

Add renewable energy

Sustainable Long Term

Reduce GHG Emissions

Invest in Alternative
Energy Technology
Bio-Mass Gasification

Integrated
Forest Products
Company

Sequestration
Afforestation
Reforestation
Product Storage

Minimize Waste

Optimize Recycling

Energy Efficient

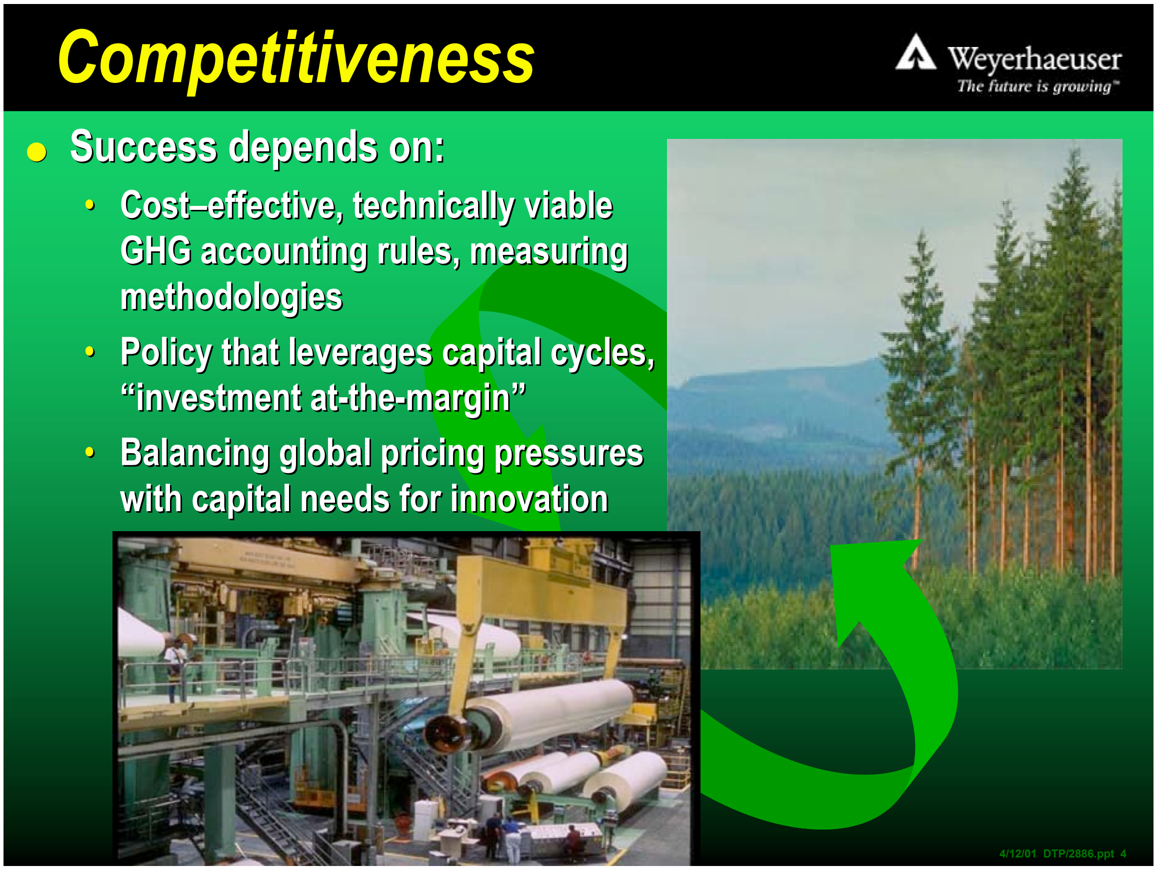
+

Bio-Mass Fuel

Co-Gen (CHP)

Conserve Resources

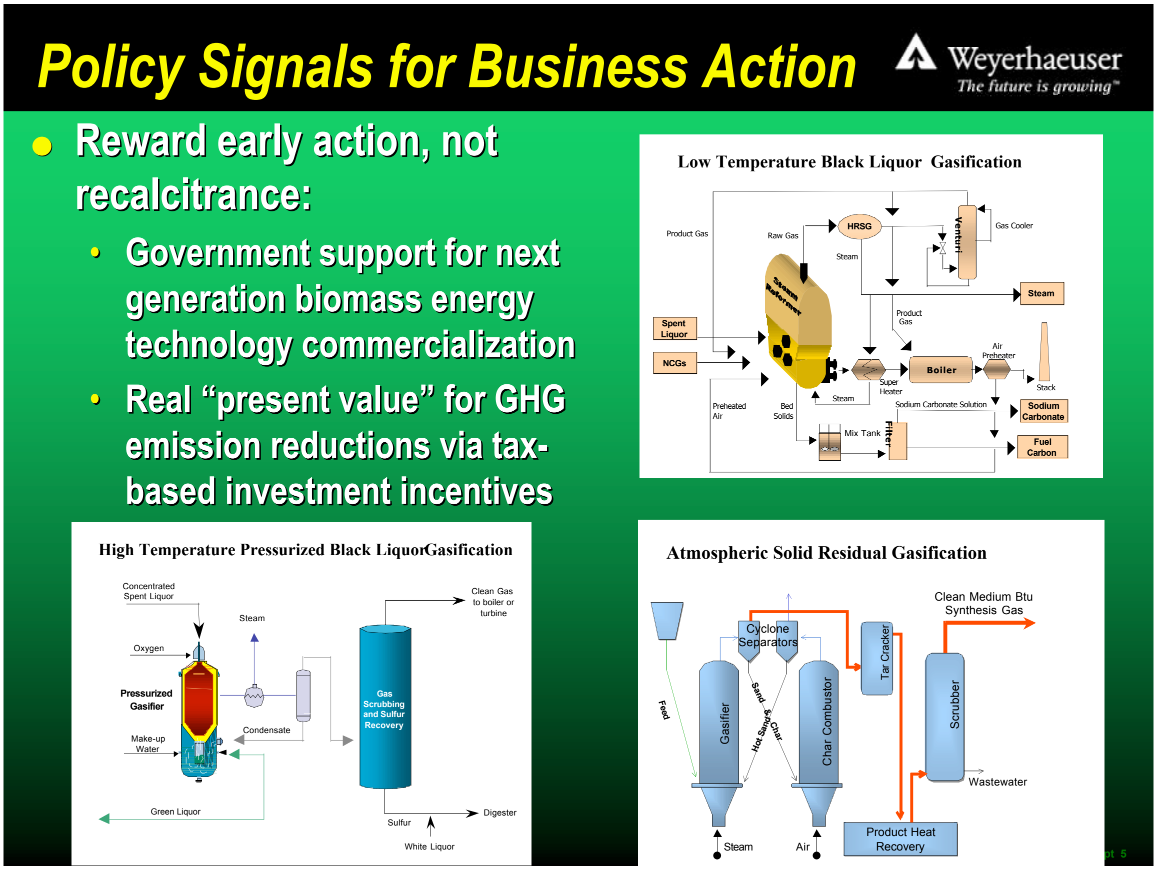
Sustainable Forestry



Competitiveness

Weyerhaeuser
The future is growing™

- Success depends on:
  - Cost–effective, technically viable GHG accounting rules, measuring methodologies
  - Policy that leverages capital cycles, "investment at-the-margin"
  - Balancing global pricing pressures with capital needs for innovation



Policy Signals for Business Action

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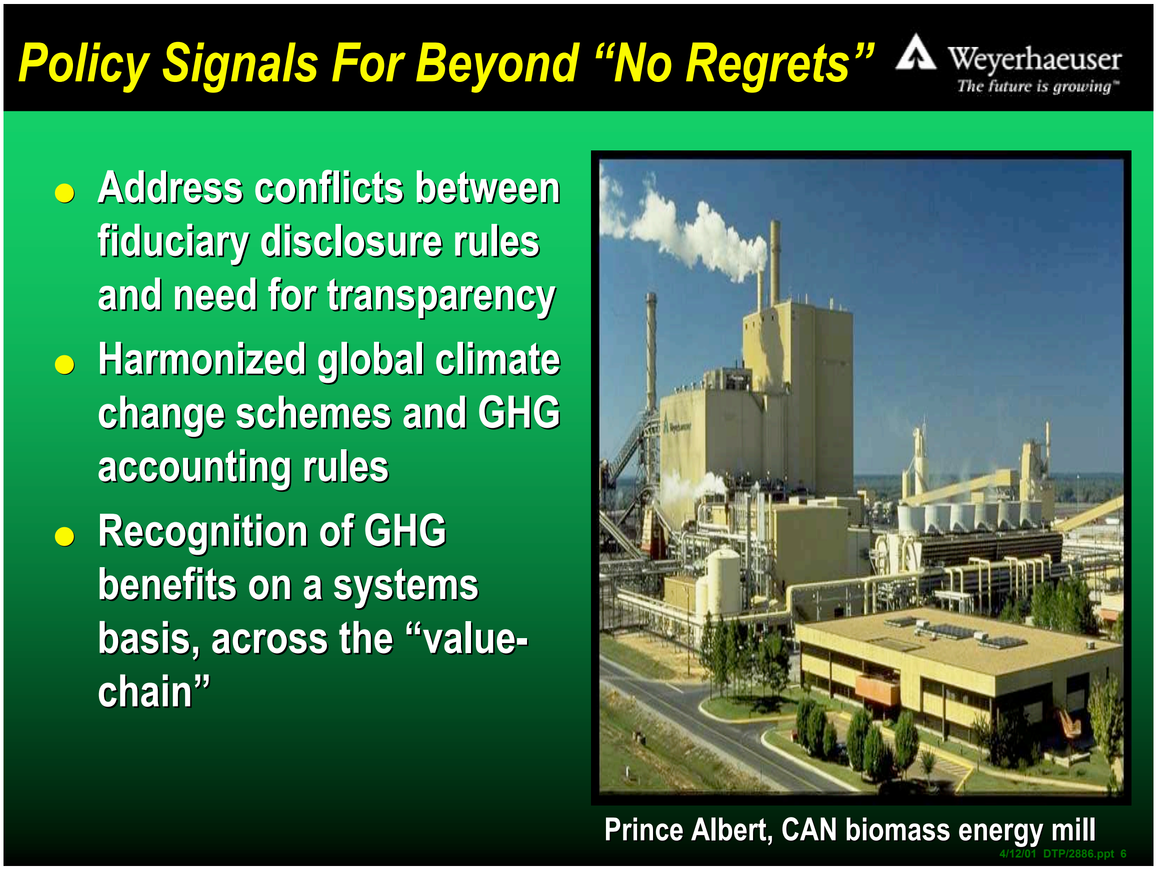
- Reward early action, not recalcitrance:
  - Government support for next generation biomass energy technology commercialization
  - Real "present value" for GHG emission reductions via tax-based investment incentives

Low Temperature Black Liquor Gasification

High Temperature Pressurized Black LiquorGasification

Atmospheric Solid Residual Gasification



Policy Signals For Beyond "No Regrets"

Weyerhaeuser
The future is growing™

- Address conflicts between fiduciary disclosure rules and need for transparency
- Harmonized global climate change schemes and GHG accounting rules
- Recognition of GHG benefits on a systems basis, across the "value-chain"

Prince Albert, CAN biomass energy mill

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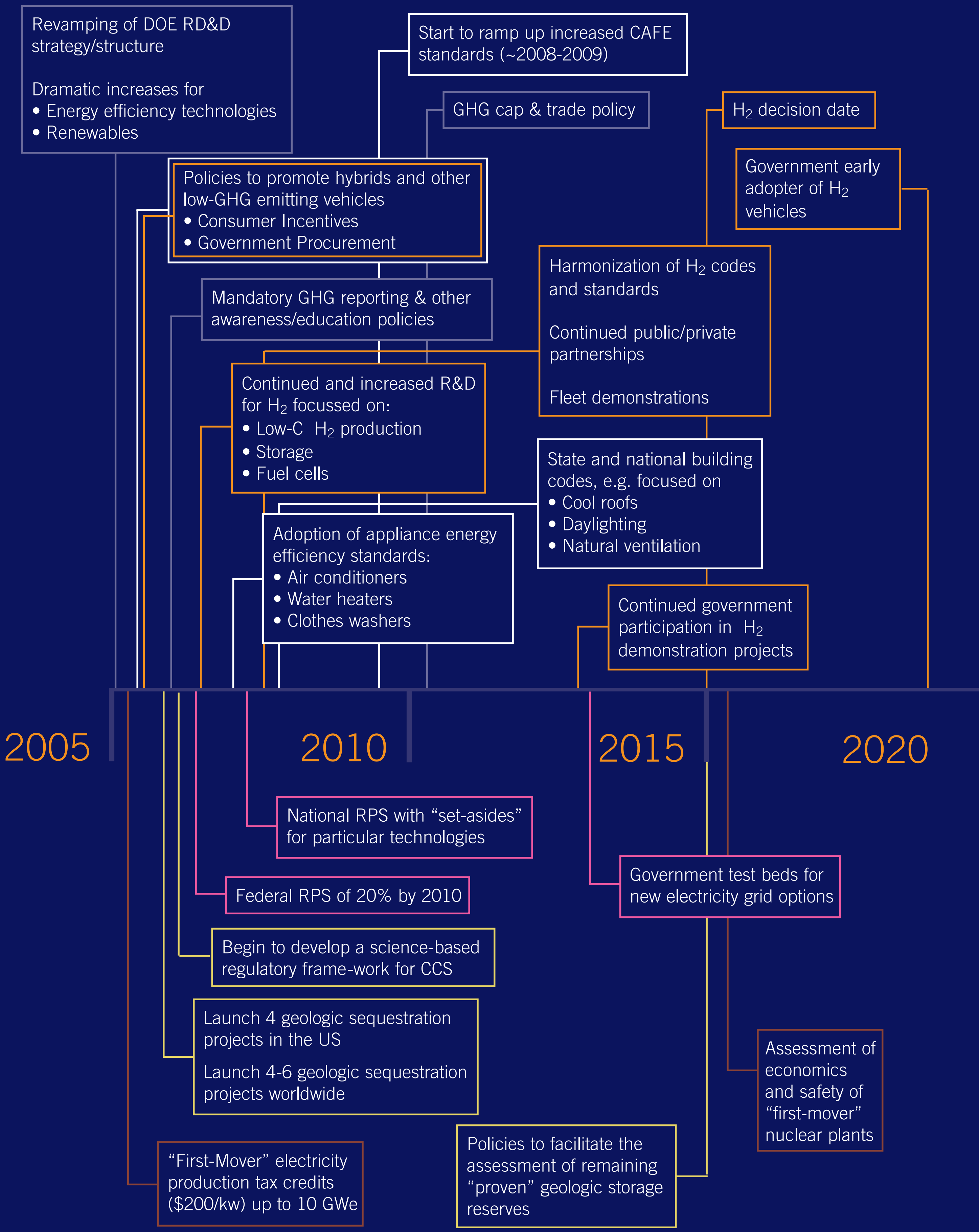


Revamping of DOE RD&D strategy/structure

Dramatic increases for
- Energy efficiency technologies
- Renewables

Start to ramp up increased CAFE standards (~2008-2009)

GHG cap & trade policy

H_2 decision date

Government early adopter of H_2 vehicles

Policies to promote hybrids and other low-GHG emitting vehicles
- Consumer Incentives
- Government Procurement

Harmonization of H_2 codes and standards

Continued public/private partnerships

Fleet demonstrations

Mandatory GHG reporting & other awareness/education policies

Continued and increased R&D for H_2 focussed on:
- Low-C H_2 production
- Storage
- Fuel cells

State and national building codes, e.g. focused on
- Cool roofs
- Daylighting
- Natural ventilation

Adoption of appliance energy efficiency standards:
- Air conditioners
- Water heaters
- Clothes washers

Continued government participation in H_2 demonstration projects

National RPS with “set-asides” for particular technologies

Federal RPS of 20% by 2010

Government test beds for new electricity grid options

Begin to develop a science-based regulatory frame-work for CCS

Launch 4 geologic sequestration projects in the US

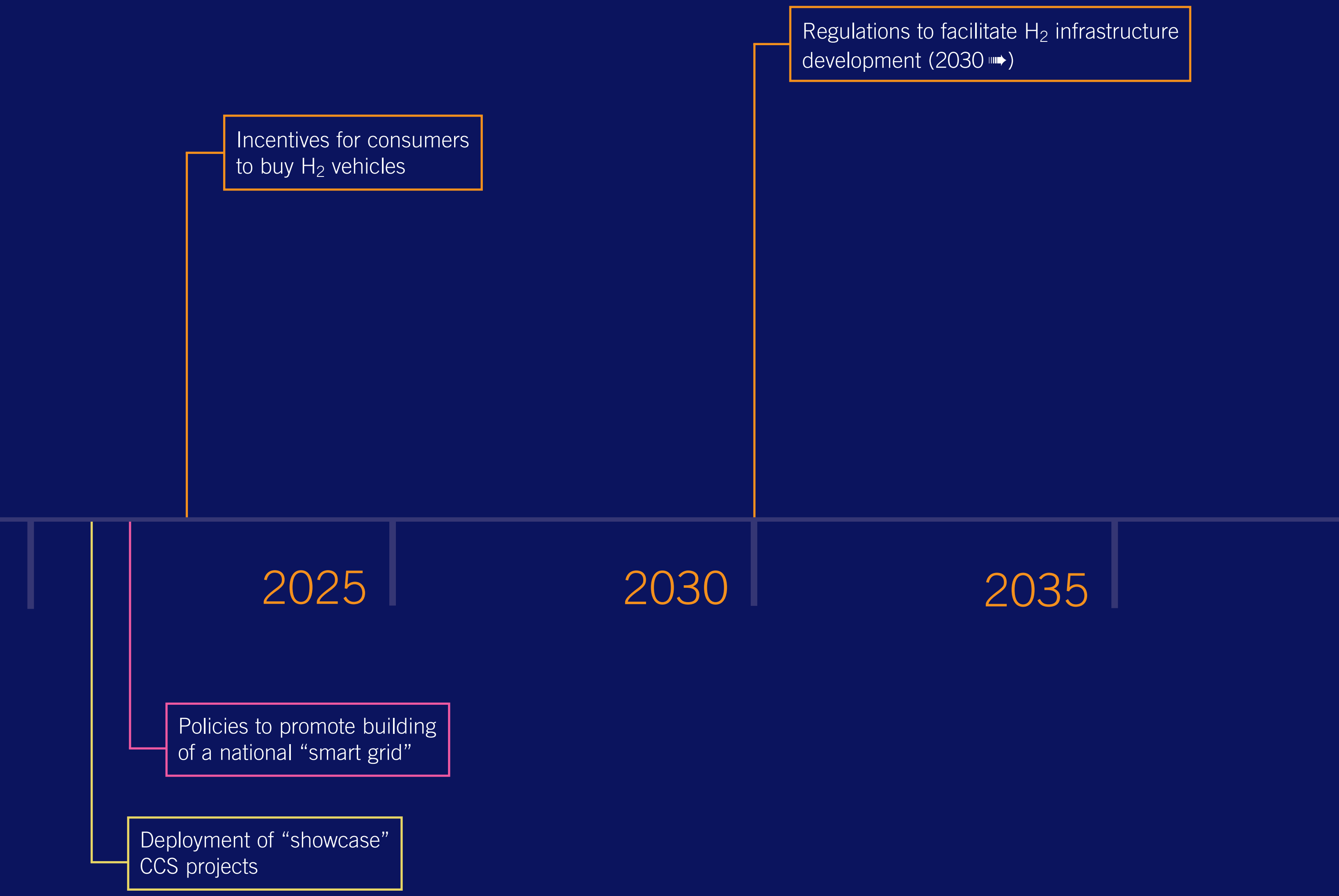
Launch 4-6 geologic sequestration projects worldwide

Assessment of economics and safety of “first-mover” nuclear plants

Policies to facilitate the assessment of remaining “proven” geologic storage reserves

“First-Mover” electricity production tax credits ($200/kw) up to 10 GWe

Figure 2: Policy Options for a Low-Carbon Future



Significant GHG reduction target

This figure describes various policy proposals put forth by workshop participants. A mix of these policies, plus others yet to be defined, will probably be necessary to enable the development and deployment over time of the technologies described in Figure 1.

Numerous policy proposals suggested in workshop papers and discussions focused on the next 10 to 15 years, and very few aimed beyond the 2015–2020 time frame. This more limited focus can be attributed partly to a hesitancy to offer policy prescriptions in the face of technological (and other) uncertainties, but it also reflects the widespread sentiment of the 10-50 Workshop participants: it is imperative to start now to develop technologies that will enable a low-carbon economy by 2050.

The integration of Figures 1 and 2 shows that a suite of policies must be enacted in the near term to enable continuous incremental reductions in GHG emissions through deployment of these technologies and to better position society to select among low-carbon options in the future.

2040 2045 2050 2055

KEY

— Cross-cutting Policies
— Efficiency
— Hydrogen
— Carbon Sequestration/Coal Gasification
— Nuclear
— Renewables

The Pew Center on Global Climate Change is a non-profit, non-partisan, independent organization dedicated to providing credible information, straight answers, and innovative solutions in the effort to address global climate change.

The National Commission on Energy Policy is a bipartisan group of leading energy experts who have come together to develop a long-term U.S. energy strategy that promotes national security, economic prosperity, and environmental safety and health. The Commission has issued two interim studies and will release its final report in late 2004.