September 23, 1997

The Honorable Federico Peña
Secretary of Energy
Forrestal Building
1000 Independence Ave., SW
Washington, D.C. 20585

Dear Mr. Secretary:

Technology Opportunities to Reduce U.S. Greenhouse Gas Emissions

The national laboratory directors are delivering our report responding to your request that we identify cost-effective technological means to reduce greenhouse gas emissions. This study reinforces our belief that science and technology are key elements in any climate change strategy.

The technology opportunities outlined in this report are intended to serve as input to broader efforts to develop an integrated national climate change strategy. The climate change issue is highly complex and multidimensional. Considerable work remains to be done in determining which technologies are most promising and what the requirements are to further evaluate and undertake the development and deployment of these technologies.

We greatly appreciate the hard work by our friends and colleagues in developing the necessary information and preparing this report on a compressed schedule. We believe that this multi-lab effort represents a mode of cooperation and collaboration that will set a pattern for future efforts by industry, government, universities, and the Department's national laboratories.

Thank you for the privilege of allowing us to lead this effort.

Sincerely,

Alvin W. Trivelpiece, Co-chair
Oak Ridge National Laboratory

John C. Browne
Los Alamos National Laboratory

Richard H. Truly, Co-chair
National Renewable Energy Laboratory

Charles V. Shank
Lawrence Berkeley National Laboratory

Dean E. Eastman
Argonne National Laboratory

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Peter D. Bond
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William J. Madia
Pacific Northwest National Laboratory

Rita A. Bajura
Federal Energy Technology Center

C. Paul Robinson
Sandia National Laboratories

Barton Krawetz
Idaho National Engineering and Environmental Laboratory

The Secretary of Energy

Washington, D.C.

April 22, 1998

Dr. Alvin Trivelpiece
Director, Oak Ridge National Laboratory
P.O. Box 2008, Mail Stop 6255
Oak Ridge, Tennessee 37830

Admiral Richard H. Truly
Director, National Renewable Energy Laboratory
U.S. Department of Energy
1617 Cole Boulevard
Golden, Colorado 80401

Dear Dr. Trivelpiece and Admiral Truly:

Thank you for responding to my request for evaluating technology pathways to reduce greenhouse gas emissions with sustained economic growth. President Clinton framed this issue in his June 1997 United Nations speech, when he said

> In order to reduce greenhouse gases and grow the economy, we must invest more in the technologies of the future. I am directing my cabinet to work to develop them. Government, and universities, business and labor must work together. All these efforts must be sustained over years, indeed over decades.

I am pleased to receive your report, *Technology Opportunities to Reduce U.S. Greenhouse Gas Emissions,* and ask that you convey my gratitude to all your colleagues who contributed to it.

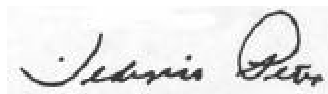
Your report, together with that of the President's Committee of Advisors on Science and Technology, will help significantly as we shape the Department's R&D portfolio in response to evolving environmental, economic, and security concerns. It is particularly valuable to have the detailed information that you provide on each of the technologies, including the current status, specific actions being taken now, and the long-term potential for energy savings and emissions reductions.

As your report indicates, substantial further analysis is needed. First, we need to prioritize our increased R&D investments to lay the foundation for future breakthroughs, to accelerate introduction of new technologies, and to complement and stimulate private sector research, development, and deployment. Also, as stated in the report, it is fortuitous that many of these technologies have already been supported by the Administration and Congress in recent years for their broader environmental and economic benefits. For the most promising pathways, the Department, under the auspices of the R&D Council, will work with stakeholders to produce technology road maps. Your report provides an excellent foundation for this activity, and your assistance will be sought together with that of academia and the private sector. The road maps will themselves evolve over time in the face of new challenges and opportunities. In addition, all proposals for increased R&D will be evaluated in the context of the complete portfolio of programs designed to spur innovation and meet environmental, economic, and national security goals.

Second, I recognize that your efforts focused solely on the technology pathways, as requested, and that due to the timing of your work, the funding views included in the report were developed in the absence of information about the tax and other policy aspects of the Administration's program. The synergies between such incentive approaches and increased research and development will help shape the optimal technology development investments. Nevertheless, many of the research priorities your group identified are reflected in the President's Fiscal Year 1999 Budget, and as we move forward, we will fold your work into the broader policy context in order to achieve long-term greenhouse emission reductions in the most cost effective manner.

I am optimistic that the Department of Energy Laboratories, together with our partners in the private sector and in academia, will make significant contributions to clean and affordable energy sources that meet America's environmental goals for the twenty-first century. I look forward to working with you toward that end.

Sincerely,



Federico Peña

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Dr. C. Paul Robinson, President and Laboratories Director
Sandia National Laboratories

TECHNOLOGY OPPORTUNITIES TO REDUCE U.S. GREENHOUSE GAS EMISSIONS

October 1997

Prepared by

National Laboratory Directors
for the
U.S. Department of Energy

On the World Wide Web:
http://www.ornl.gov/climate_change

PREFACE

President Clinton directed his cabinet to respond to the challenge of reducing greenhouse gas emissions in the United States. In turn, Secretary of Energy Peña asked the directors of 11 of the Department of Energy's national laboratories to identify technologies that could be used to meet this challenge. In response to this request, scientists and engineers from the Department's national laboratories built upon existing collaborations with technical leaders from industry, government, and universities in doing the work that led to the findings and conclusions reported here. In pursuing the goal of identifying cost-effective means to reduce greenhouse gas emissions, the following questions were used as guidelines:

> What technologies can be improved through research and development (R&D), which are not now deployed or utilized extensively?
>
> What are those new technologies that could be developed in the future, with reasonable effort and cost?
>
> What is the program of research and development which is needed to bring about these results?

In our efforts to answer these questions, we have taken the position that the development of a science-based, cost-effective technological means to reduce greenhouse gas emissions is a prudent step to take independent of the outcome of the continuing scientific debate on the subject of global climate change.

We believe that this report serves as the technology basis of a needed national climate change technology strategy, with the confidence that a strong technology R&D program will deliver a portfolio of technologies with the potential to provide very substantial greenhouse gas emission reductions along with continued economic growth. Much more is needed to define such a strategy, including identification of complementary deployment policies and analysis to support the scoping and prioritization of R&D programs. A national strategy must be based upon governmental, industrial, and academic partnerships.

In the final analysis, a combination of well-conceived national policy and the concurrent development of advanced technologies will be needed to achieve the nation's dual strategic goals of reducing greenhouse gas emissions and maintaining a robust economy. While our task was to focus on technology, and not on government policy, we recognize this important link.

We are honored to have been asked to lead this effort. We want to thank all of those who participated in the work upon which this report is based.

CONTENTS

FIGURES

TABLES

ACRONYMS, ABBREVIATIONS, AND INITIALISMS

ATS	advanced turbine system
C	carbon
C/E	carbon intensity
CFC	chlorofluorocarbon
CH_4	methane
CO_2	carbon dioxide
CRADA	cooperative research and development agreement
DOE	U.S. Department of Energy
E/GDP	energy per unit of economic output
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
EV	electric drive vehicles
FCCC	Framework Convention on Climate Change
FTTA	Federal Technology Transfer Act
GDP	gross domestic product
GHG	greenhouse gas
GRI	Gas Research Institute
GtC	gigatons of carbon (10^3 million tons)*
GW	gigawatt (10^3 MW)
GWe	gigawatt electric
HCFC	hydrochlorofluorocarbon
HEV	hybrid electric vehicles
HHV	high heat value
HVAC	heating, ventilation, and air conditioning
HVDC	high voltage direct current
IGCC	integrated gasification combined cycle
I/O	input/output
IOF	Industries of the Future
IPCC	Intergovernmental Panel on Climate Change
kWh	kilowatt hour

*A tonne, or metric ton, is 1000 kilograms or about 2200 lb.

LEGO	lifetime extension and generation optimization
LIDAR	light detection and ranging
low-E	low emissivity
mpg	miles per gallon
mph	miles per hour
MSW	municipal solid waste
MtC	million metric tons of carbon
MWe	megawatt = 10^6 watt, electric
MWt	megawatt thermal
NA	not applicable
NASA	National Aeronautics and Space Administration
NCRA	National Cooperative Research Act
NFRC	National Fenestration Rating Council
NGO	nongovernmental organization
NO_x	nitrogen oxides
NRC	Nuclear Regulatory Commission
OBTS	U.S. DOE Office of Building Technology, State and Community Programs
OI	other industrial
OIT	U.S. DOE Office of Industrial Technologies
ORTA	Office of Research and Technology Application
PEM	proton exchange membrane
PNGV	Partnership for a New Generation of Vehicles
ppmv	parts per million by volume
PV	photovoltaic
PVMat	Photovoltaic Manufacturing Initiative
quad	quadrillion (10^{15}) Btus
R&D	research and development
RD&D	research, development, and demonstration
SBIR	Small Business Innovation Research
scf	standard cubic feet
SEMATECH	Semiconductor Manufacturing Technology
SMES	superconducting magnetic energy storage
SOM	soil organic matter
Tcf	trillion cubic feet
TRP	Technology Reinvestment Project
TWh	terawatt hour (terawatt = 10^6 MW)
USCAR	United States Council for Automotive Research
USDA	U.S. Department of Agriculture
USGCRP	U.S. Global Change Research Program

EXECUTIVE SUMMARY

The rise in greenhouse gas emissions from fossil fuel combustion and industrial and agricultural activities has aroused international concern about the possible impacts of these emissions on climate. Greenhouse gases—mostly carbon dioxide, some methane, nitrous oxide and other trace gases—are emitted to the atmosphere, enhancing an effect in which heat reflected from the earth's surface is kept from escaping into space, as in a greenhouse. Thus, there is concern that the earth's surface temperature may rise enough to cause global climate change.

Approximately 90% of U.S. greenhouse gas emissions from anthropogenic sources come from energy production and use, most of which are a byproduct of the combustion of fossil fuels. On a per capita basis, the United States is one of the world's largest sources of greenhouse gas emissions, comprising 4% of the world's population, yet emitting 23% of the world's greenhouse gases. Emissions in the United States are increasing at around 1.2% annually, and the Energy Information Administration forecasts that emissions levels will continue to increase at this rate in the years ahead if we proceed down the business-as-usual path.

President Clinton has presented a two-part challenge for the United States: reduce greenhouse gas emissions and grow the economy. Meeting the challenge will mean that in doing tomorrow's work, we must use energy more efficiently and emit less carbon for the energy expended than we do today. To accomplish these goals, President Clinton proposed on June 26, 1997, that the United States "invest more in the technologies of the future."

In this report to Secretary of Energy Peña, 47 technology pathways are described that have significant potential to reduce carbon dioxide emissions. The present study was completed before the December 1997 United Nations Framework Convention on Climate Change and is intended to provide a basis to evaluate technology feasibility and options to reduce greenhouse gas emissions. These technology pathways (which are described in greater detail in Appendix B, Technology Pathways) address three areas: energy efficiency, clean energy, and carbon sequestration (removing carbon from emissions and enhancing carbon storage). Based on an assessment of each of these technology pathways over a 30-year planning horizon, the directors of the Department of Energy's (DOE's) national laboratories conclude that success will require pursuit of multiple technology pathways to provide choices and flexibility for reducing greenhouse gas emissions. Advances in science and technology are necessary to reduce greenhouse gas emissions from the United States while sustaining economic growth and providing collateral benefits to the nation.

Fortunately, many of these technologies are already the subject of some federally sponsored and private-sector research, development, and demonstration (RD&D) driven by the collateral benefits they offer. It is worth noting that DOE's applied energy technology programs are already supporting the development of many of the requisite technologies or elements of these technologies (see Appendix B). Similarly, DOE's Office of Energy Research funds basic research in areas that underpin the applied energy technology programs. If developed and widely used, these technologies would also improve air quality, reduce U.S. dependence on imported oil, and increase exports of U.S. technologies to help other nations reduce their greenhouse gas emissions while growing their economies, all of which will sustain national economic growth.

We believe that developing technology solutions sooner rather than later will be more effective in reducing greenhouse gas emissions. Postponing action could close technology options or increase future costs and risks. The laboratory directors and DOE recognize that supportive programs and policies will also be critical to bringing new technologies into the marketplace. New policies and programs to deal with emissions may be needed, such as subsidies or tax incentives or permit trading programs to encourage accelerated adoption of energy efficiency or clean energy technologies. However, these programs and policies are not specified in this study. In addition, the technology pathways are not prioritized in this report in terms of potential for commercialization or research and development (R&D) funding. Further analysis is required to accomplish that.

Our findings suggest that each decade is distinct in terms of the range of greenhouse gas reduction technologies that could be available.

- In the first decade, significant advances in energy efficiency technologies would deliver substantial near-term carbon-reducing impacts by decreasing the energy intensity (amount of energy used to do work) of the U.S. economy. Clean energy technologies would continue to grow, and carbon sequestration technologies could begin to emerge.
- Along with continued improvements in energy efficiency, research-based advances in clean energy technologies would reduce significantly the carbon intensity (amount of carbon emitted for the energy used) of the U.S. energy economy during the second decade. A wide range of improved renewable, fossil, and nuclear technologies could be introduced and widely deployed in this period. These clean energy options could begin to exceed the carbon reduction impact of increased end-use efficiencies by the year 2025.
- Complementing ongoing advances in clean energy and efficiency technologies well into the third decade, carbon sequestration technologies would add a third important dimension to the package of solutions. Success in this technology area could enable the nation to continue its extensive use of fossil fuels without harming the global climate. We assume that these technologies would not be widely available until the 2030 time frame; however, successful introduction earlier could result in significantly greater reductions in net carbon emissions.

We believe that by 2030, a vigorous RD&D program could deliver a wide array of cost-effective technologies that together could reduce the nation's carbon emissions by 400–800 million metric tons of carbon (MtC) per year. This decrease represents a significant portion of the carbon emission reductions that may be targeted by the United States for 2030. Additional reductions would result from the implementation of new policies and deployment programs, particularly in early years when the market penetration of existing and near-term technologies could be accelerated.

Possible goals for an RD&D program are presented below, along with some of the technologies that could contribute to achieving them.

Energy Efficiency

- Use electricity more efficiently through the deployment of advanced technologies (e.g., intelligent building control systems, cost-effective refrigerators that use half as much electricity as today's models, and fuel cells for heat and power in commercial buildings).
- Reduce use of gas and oil for space and water heating through building efficiency measures (e.g., super insulation, gas-fired heat pumps that provide highly efficient space heating and cooling, and building envelopes that capture and store solar energy for later use).
- Improve industrial resource recovery and use (e.g., develop an integrated gasification combined cycle power technology, which can convert coal, biomass, and municipal wastes into power and products) and industrial processes to save energy (e.g., advanced catalysis and separations technologies).
- Increase transportation efficiency through new technologies (e.g., a hybrid electric vehicle that is three times more fuel-efficient than today's standard model).

Clean Energy

- Change the energy mix to increase use of sources with higher generating efficiencies and lower emissions—increased use of natural gas, safer and more efficient nuclear power plants, renewable energy (e.g., solar and wind power; electricity and fuels from agricultural biomass), and hydrogen (to produce electricity through fuel cells).
- Develop "energyplexes" that would use carbon efficiently without emitting greenhouse gases for the integrated production of power, heat, fuels, and chemicals from coal, biomass, or municipal wastes.
- Distribute electricity more efficiently to reduce emissions (e.g., distributed generation using superconducting transformers, cables, and wires).
- Switch transportation to energy sources with lower emissions (e.g., trucks that run on biodiesel fuel; ethanol from cellulosic feedstocks).
- Remove carbon from fuels before combustion.

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Carbon Sequestration

- Efficiently remove carbon dioxide from combustion emissions before they reach the atmosphere.
- Increase the rate at which oceans, forests, and soils naturally absorb atmospheric carbon dioxide.
- Develop technologies for long-term carbon storage in geological deposits, aquifers, or other reservoirs.

Basic and Applied Research Are Needed

Meeting the goals described above also depends upon incremental improvements and breakthroughs in the basic sciences. For example, basic research is needed to

- understand the global carbon cycle (i.e., computational modeling and measurements to understand the ocean–atmosphere–terrestrial biosphere interactions) and judge the benefits and risks of sequestration options
- support greenhouse gas reduction technologies (i.e., materials, chemical sciences, biotechnology, geosciences, environmental and ecological sciences, nuclear sciences, and computational sciences)

To support multiple technology pathways, enabling technologies also must be improved, especially transmission/distribution systems that deliver energy faster and more efficiently. Relevant enabling technologies include

- hydrogen production, storage, and distribution
- fuel cells
- electricity transmission, distribution, and components
- sensors and controls
- energy storage systems

Strategic Alliances Are Essential

Strategic public–private alliances provide the best approach for developing and deploying most greenhouse gas reduction technologies. Although many of these technologies will be able to compete cost-effectively in the marketplace in the future, industry is unlikely to lead and fully finance the innovation process because of the high risk associated with developing technologies that will not be deployed for decades, and because the market currently does not place a high value on carbon mitigation. Using public–private strategic alliances will help maximize the efficiency of the innovation process by bringing together stakeholders who are capable of overcoming the relevant scientific, technical, and commercial challenges.

Research, Development, and Demonstration Resources

This report describes the carbon emission reductions that could result from an accelerated RD&D program. It does not consider collateral benefits from initiating complementary deployment programs or policies aimed at stimulating markets for greenhouse gas reduction technologies. It is believed that an integrated approach (i.e., science and technology in combination with deployment programs and supporting policies) is the most cost-effective one.

To achieve the annual emission reductions of 400 to 800 MtC by 2030 described in this report, federal RD&D budget increments would be necessary in three areas:

- the development of advanced energy technologies
- the development of carbon sequestration technologies, including supporting research on carbon cycle modeling and ecosystems

- the basic research areas that are the wellspring of future technological breakthroughs.

Moving Forward

The laboratory directors recommend that the United States develop and pursue a detailed and comprehensive technology strategy for reducing greenhouse gas emissions. By summarizing the status, potential, and fundamental research needs of a broad range of technologies relevant to reducing greenhouse gas emissions, this report provides one key element, namely, the technology basis, for developing a climate change technology strategy. However, full definition of such a strategy requires several additional steps, especially an assessment of alternative programs and policies to promote deployment and an analysis of the costs and benefits of alternative technology and policy options to develop priorities. Further, we propose that DOE lead the development of this strategy because of its energy technology mission, its proven record in developing major national initiatives, and the attendant strategic alliances that are needed to solve complex national problems where science makes a difference. When implemented through focused public–private strategic alliances, this strategy should lead to technological advances that have broad market appeal. We believe that such a technology strategy could significantly reduce U.S. greenhouse gas emissions. Achieving this challenging goal while sustaining economic growth would require a vigorous RD&D program sustained by strong partnerships among government, universities, and the private sector.

In summary, this report concludes that a national investment in a technology RD&D program over the next three decades would provide a portfolio of technologies that *could* significantly reduce greenhouse gas emissions over the next three decades and beyond. To make effective progress against realistic goals and expectations, an outlay of approximately $1B/year above those presently dedicated to these efforts would be a prudent investment of resources. We believe that many technological opportunities exist that could *significantly contribute to* this goal without harming the nation’s economy. A strategic plan that includes deployment policies to complement technology RD&D will be necessary for success. Plans will need to be formulated that reflect both the economic and technological implications of deploying these technologies. Hence, development of a climate change technology strategy is the recommended next step. The development process should include review of technology policy options to complement technology development options, and a detailed plan for supporting implementation which addresses technology goals, RD&D program plans, policies that support deployment, and fiscal resources. Development of this RD&D agenda should be a collaborative effort between government, industry, business, and the scientific communities. The implementation of a technology strategy to reduce greenhouse gas emissions will serve as an investment insurance policy. It should reduce the threat of climate change from fossil fuel use and provide acceptable technologies that produce savings and revenues that would far exceed the cost of an accelerated research program. The DOE’s national laboratories stand ready to champion this enterprise.