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Summary of Testimony for the September 20,2006 Hearing on:

The U.S. Climate Change Technology Program Strategic Plan

by

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Introduction
Chairwoman Biggert and members of the House Committee on Science, I am grateful for the opportunity today to speak with you on the critical issue of the United States' approach to the great challenges that climate change presents our nation and the planet. At the heart of my comments is the finding that leadership in protecting the environment and improving our economic and political security can be achieved not at a cost, but through political and economic gain to the nation in the form of reasserted leadership both technologically and financially, through increased geopolitical stability and flexibility, and through job growth in the 'clean energy' sector.

I hold the Class of 1935 Distinguished Chair in Energy at the University of California, Berkeley, where I am a professor in the Energy and Resources Group, the Goldman School of Public Policy, and the Department of Nuclear Engineering. I am the founding director of the Renewable and Appropriate Energy Laboratory, an interdisciplinary research unit that explores a diverse set of energy technologies through scientific, engineering, economic and policy issues. I am also the Co-Director of the University of California, Berkeley Institute of the Environment. I have served on the Intergovernmental Panel on Climate Change (IPCC), and have testified before both U. S. House and Senate Committees on the science of regional and global climate change, and on the technical and economic status and the potential of a wide range of energy systems, notably renewable and energy efficiency technologies for use in both developed and developing nations. I am the author of over 160 research papers, and five books, most of which can be found online at http://socrates.berkeley.edu/~rael.

In July of last year the Honourable R. John Efford, the then Minister of Natural Resources Canada, announced my appointment, as the only U. S. citizen, to serve on the Canadian National Advisory Panel on the Sustainable Energy Science and Technology (S&T) Strategy. The Panel provides advice on energy science and technology priorities to help Canada develop sustainable energy solutions, and is tasked to produce a document similar in objectives to the Climate Change Technology Program Strategic Plan, which we are here today to discuss.

Overview of Climate Change and Innovation in the Energy Sector

As described in the CCTP Strategic Plan climate change presents our nation with a serious, long-term challenge. Central to the difficulty of this challenge is that reducing the risks posed by climate change will require us to transform the largest industry on the planet, the energy industry. Energy is important, not only for its direct contribution to 10% of economic output by our nation's private sector, but also as the fundamental enabling infrastructure for an array of economic activities, from manufacturing to agriculture to healthcare. The availability of reliable and affordable energy should not be taken for granted. The challenges of renewing the U.S. energy infrastructure to enhance economic and geopolitical security and prevent global climate change are particularly acute, and depend on the improvement of existing technologies as well as the invention, development, and commercial adoption of emerging ones. Recent trends in the energy sector—which show declining levels of technology investment and innovation—heighten the need for an aggressive response (Appendix A). The CCTP provides a tremendous opportunity to reverse this trend, open up new technological options, and stimulate economic growth through the development of a new clean energy-based sector of the economy. Key strengths of the CCTP Strategic Plan are its leadership by the President, the acknowledgement of the long-term nature of the problem, and the breadth of its technology portfolio. Yet the CCTP Strategic Plan, in its current draft, is seriously flawed. The goal that it seeks to reach, and the basis on which we are here to evaluate it today, is far too modest; it is not commensurate with the magnitude of the challenges we face and not reflective of our nation's capacity for innovation. This testimony will outline the magnitude of effort that will be required, an overview of the innovation environment in the energy sector, and recommendations for improvement.

The nation's climate technology program should be based on a goal that reduces emissions

The most significant shortcoming of the CCTP strategic plan is that the goal it seeks to reach is not commensurate with the magnitude of the challenges posed by climate change and other energy-related problems. In evaluating the CCTP strategic plan one must first seriously consider what goal it is trying to achieve. To avoid the adverse impacts of climate change we will need to stabilize concentrations of greenhouse gases in the atmosphere. This will require real reductions in the amount of carbon dioxide and other greenhouse gases that we emit. As the strategic plan itself asserts:

> Stabilizing GHG concentrations, at any atmospheric concentration level, implies that global *additions* of GHGs to the atmosphere and global *withdrawals* of GHGs from the atmosphere must come into a net balance. This means that growth of *net* emissions of GHGs would need to slow, eventually stop, and then reverse, so that, ultimately, *net* emissions would approach levels that are low or near zero." (p 2-2)

However, today we are here to evaluate the program based on its ability to meet the Administration's emissions intensity target of an 18% reduction in GHG intensity by 2012. Throughout this testimony, I will argue that a major flaw in the CCTP plan is that it is designed to meet a goal that is wholly inadequate to the challenge we face. Only when we take this challenge seriously will we be able to meaningfully mobilize our nation's scientific, technological, and economic resources to meet it, as well as to reap the benefits of international leadership in the clean and sustainable energy sector.

The need to reduce uncertainties in current climate science around climate sensitivity and expected impacts is often cited as a reason for delaying commitments to emissions reductions. Yet, the plan is correct in pointing out that scientific uncertainty is neither a valid justification nor a wise strategy for choosing to delay. In fact, there is not much uncertainty about the basic problem and its magnitude. Estimates done at Lawrence Livermore National Lab of carbon emissions which assume we find a way to reduce emissions to zero by 2050 while meeting energy service demands – i.e. very conservative estimates – will still almost certainly result in CO_2 levels exceeding 550ppm in the atmosphere, if not more. Given that the CO2 level is now 380ppm -- 30% higher than it has been at any point in the last 650,000 years-- we are essentially conducting an unprecedented experiment with the Earth. Despite the long time horizons of the climate change problem, the availability of carbon-free energy technologies is a relatively urgent matter because the 100-year residence time of CO_2 in the atmosphere, the 30 to 50-year lifetime of capital stock in the energy industry, and the typical decades-long diffusion curve for infrastructure-related technologies are to varying extents outside of our control. The response to this combination of uncertainty and urgency should be a commitment to the creation of a multitude of new technological options, not a timid approach that narrows the range of possibilities at our disposal in the future.

In contrast, meeting the Administration's current target will require only a slight change from the business as usual case (Figure 1) (EPA 2005). More relevant to the climate problem, reaching this target would actually allow emissions to grow by 12 to 16%. This target would thus represent a larger increase than the 10% increase that occurred in the previous decade. If we are to be serious about meeting the climate challenge we need to set a goal consistent with the CCTP's objective of moving toward zero net emissions. While the Kyoto Protocol has its flaws, its targets do represent a substantial shift toward reducing emissions. Similarly, the Governor of California's GHG emissions targets announced last summer include both near-term and longer-term goals that delineate a path of emissions reductions toward climate stabilization. The administration should set a series of targets that show a clear path to emissions reductions.

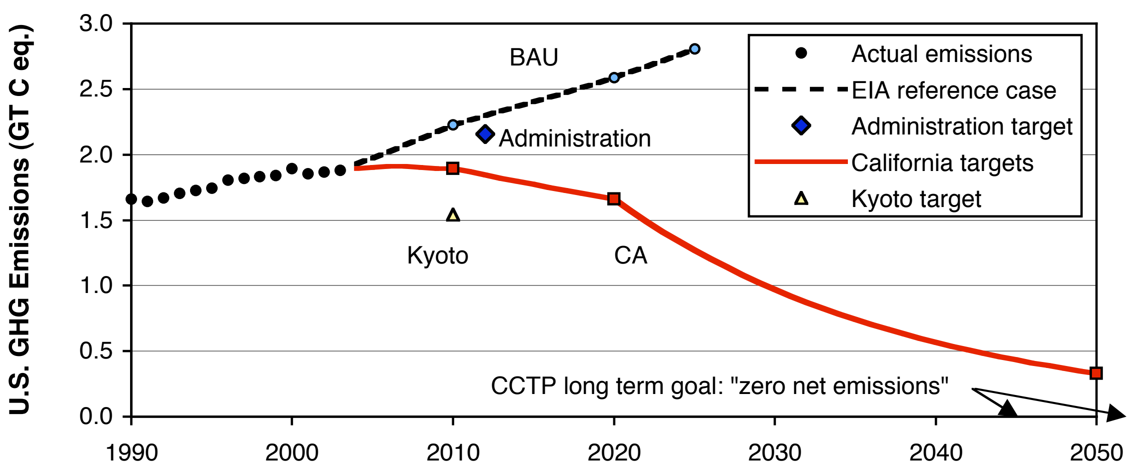

Figure 1 Historical U.S. GHG emissions and targets

Figure 1 shows actual U.S. GHG emissions from 1990 through 2003 (EPA 2005) in giga-tons of carbon equivalent. Four future paths for future U.S. emissions are shown; circles show the business-as-usual (BAU), or "reference case," as calculated by the Energy Information Agency (EIA). The diamond shows the Administration's GHG intensity target for 2012 of 18% below 2002 level in tons of carbon per unit of GDP, or a 3.6% reduction in emissions from BAU. The squares show U.S. emissions if the nation were to meet the percentage reductions that have been announced in California for 2010, 2020, and 2050 (California Executive Order 3-05, and California AB32, the "Pavley-Nuñez Bill'). The triangle shows the U.S.'s target for 2010 under the Kyoto Protocol. Arrows indicate the levels required to meet the CCTP's long-term goal of "levels that are low or near zero" (p. 2-2).

What is needed is a serious and sustained commitment to emissions reductions and a time scale that conveys to the country the urgency of the need to open future options. Much as President Nixon's announcement of a program in the early-1970s to reduce reliance on foreign oil stimulated efforts by the private sector to invest in alternative energy sources, the articulation of a bold and clear target for emissions reductions would send a signal to the private sector that would leverage the federal government's direct investments in new technologies.

Raising climate technology investment to adequate levels

In recent work, we calculated the investment in R&D required to reach a climate stabilization level of 550 ppm, a level that would double the amount of GHG in the atmosphere relative to that at the beginning of industrialization in the eighteenth century. Using emissions scenarios from the Intergovernmental Panel on Climate Change and a previous framework for estimating the climate-related savings from energy R&D programs (Schock *et al*., 1999), we calculate that U.S. energy R&D spending of $15-30 billion/year would be sufficient to stabilize CO_2 at double pre-industrial levels (see Appendix for calculations). A strategy that employs a diversified portfolio approach to manage technological uncertainty is diluted quickly when funding levels are 5 to 10 times below their socially optimal levels.

The plan itself states, "*successful development of advanced technologies could result in potentially large economic benefits*"(p. 3-28). As an example of the effect of policy on abatement costs, we can observe how a combination of R&D and demand-side policy has stimulated cost reductions in energy technologies (Duke and Kammen, 1999, Margolis and Kammen, 1999). For example, solar cells, known as photovoltaics, have declined in cost by more than a factor of 20 and wind turbines by a factor of 10. Accelerating future cost reductions in these and other technologies will require further investments in technology development and market creation.

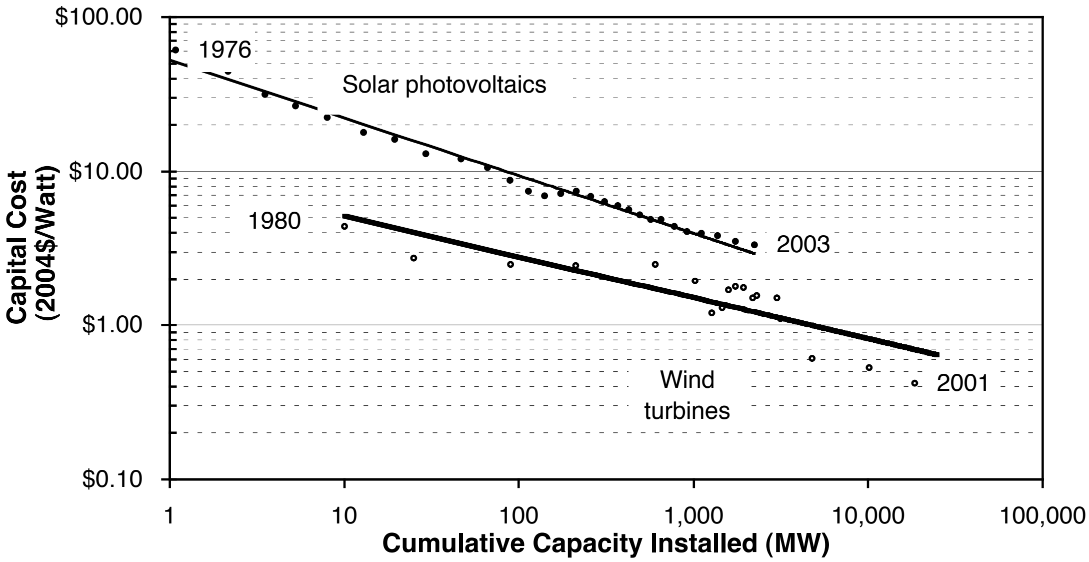

Figure 2 Cost reductions in carbon-free energy technologies

Figure 2 shows the capital costs of photovoltaics and wind turbines in constant 2004 $ per Watt. The horizontal axis shows cumulative worldwide installations of each technology (Duke and Kammen, 1999).

Climate change programs would address other problems as well

An important finding in ours and previous work on energy R&D is that many of the same programs that would help abate the climate problem would address other societal problems too. Adoption of improved zero emissions energy production and end-use technologies would offset the adverse health effects associated with emissions of mercury, sulfur dioxide, and oxides of nitrogen. Increased use of renewables-based power and fuels would reduce our sensitivity to energy production in politically unstable regions. A more distributed power system based on smaller scale production would enhance the robustness of the electricity system and reduce dangerous and costly power outages. And a more diverse mix of technologies and fuels would lessen the macro-economic effects of rapid changes in energy prices.

Comparing a major R&D initiative on climate to past programs

In our recent work we have asked how feasible it would be to raise investment to levels commensurate with the energy-related challenges we face. One way to consider the viability of such a project is to set the magnitude of such a program in the context of previous programs that this committee has participated in launching and monitoring. Scaling up R&D by 5 or 10 times from current levels is not a ‘pie in the sky’ proposal, in fact it is consistent with the scale of several previous federal programs (Table 1), each of which took place in response to a clearly articulated national need. While expanding energy R&D to five or ten times today’s level would be a significant initiative, the fiscal magnitude of such a program is well within the range of previous programs, each of which have produced demonstrable economic benefits beyond the direct program objectives.

Table 1 Comparison of energy R&D scenarios and major federal government R&D initiatives

Program	**Sector**	**Years**	**Additional spending over program duration (2002$ Billions)**
Manhattan Project	Defense	1942-45	$25.0
Apollo Program	Space	1963-72	$127.4
Project Independence	Energy	1975-82	$25.6
Reagan defense	Defense	1981-89	$100.3
Doubling NIH	Health	1999-04	$32.6
War on Terror	Defense	2002-04	$29.6
5x energy scenario	***Energy***	***2005-15***	***$47.9***
10x energy scenario	***Energy***	***2005-15***	***$105.4***

"Major R&D initiatives" in this study are federal programs in which annual spending either doubled or increased by more than $10 billion during the program lifetime. For each of these eight programs we calculate a "baseline" level of spending based on the 50-year historical growth rate of U.S. R&D, 4.3% per year. The difference between the actual spending and the baseline during the program we call additional program spending. Kammen, D. M. and G. F. Nemet (2005). "Reversing the Incredible Shrinking U.S. Energy R&D Budget." Issues in Science and Technology 22: 84-88.

Declining investment in energy R&D

My students and I have documented a disturbing trend away from investment in energy technology—both by the federal government and the private sector (Figure 3). The U.S. invests about $1 billion less in energy R&D today than it did a decade ago. This trend is remarkable, first because the levels in the mid-1990s had already been identified as dangerously low, and second because, as our analysis indicates, the decline is pervasive—across almost every energy technology category, in both the public and private sectors, and at multiple stages in the innovation process. In each of these areas investment has been either been stagnant or declining. Moreover, the decline in investment in energy has occurred while overall U.S. R&D has grown by 6% per year, and federal R&D investments in health and defense have grown by 10 to 15% per year, respectively.

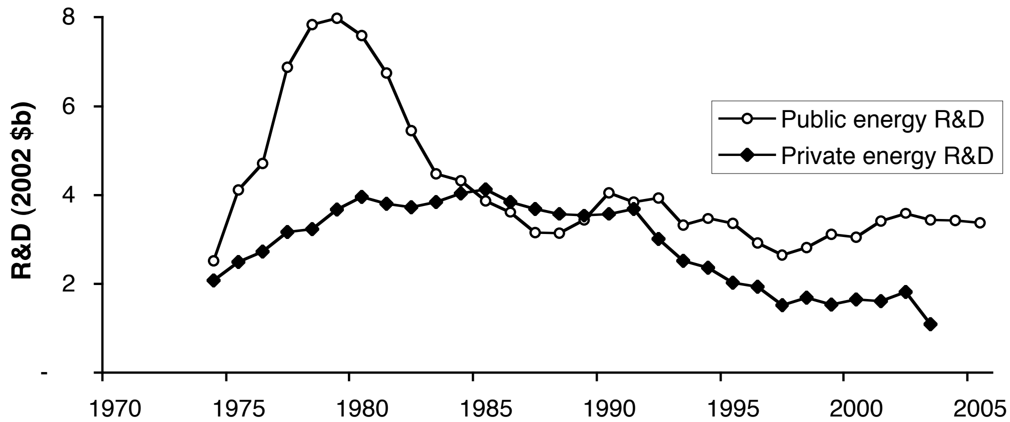

Figure 3 Declining energy R&D investment by both public and private sectors

By looking at individual energy technologies, we have found that in case after case, R&D investment spurs invention. For example, in the case of wind power patenting follows the wild swings in R&D budgets (Figure 4).

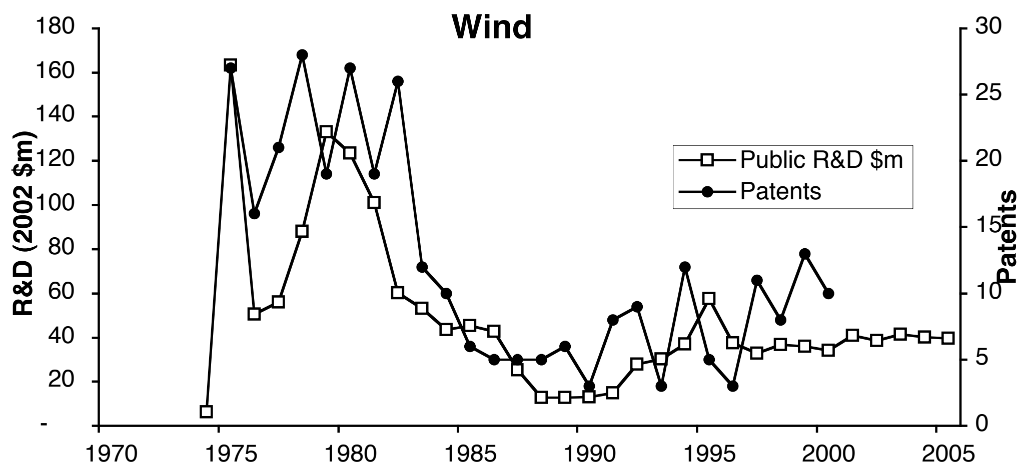

Figure 4 Federal R&D and U.S. wind power patents

A further concern regards U.S. competitiveness in these increasingly important technologies. For example, a glance at other nations' investments in new renewable energy technology shows the U.S. playing a secondary role (see Appendix C). Both Europe and Japan are investing more in R&D for renewable energy. Moreover, they have established leading companies in the fast growing wind and solar industries. Our economic competitiveness in these increasingly important sectors hinges on our commitment to investing in new technologies.

Finally, the drug and biotechnology industry provides a revealing contrast to the trends seen in energy. Although energy R&D exceeded that of the biotechnology industry 20 years ago, today R&D investment by biotechnology firms is an order of magnitude larger than that of energy firms (Figure 5). Today, total private sector energy R&D is less than the R&D budgets of individual biotech companies such as Amgen and Genentech.

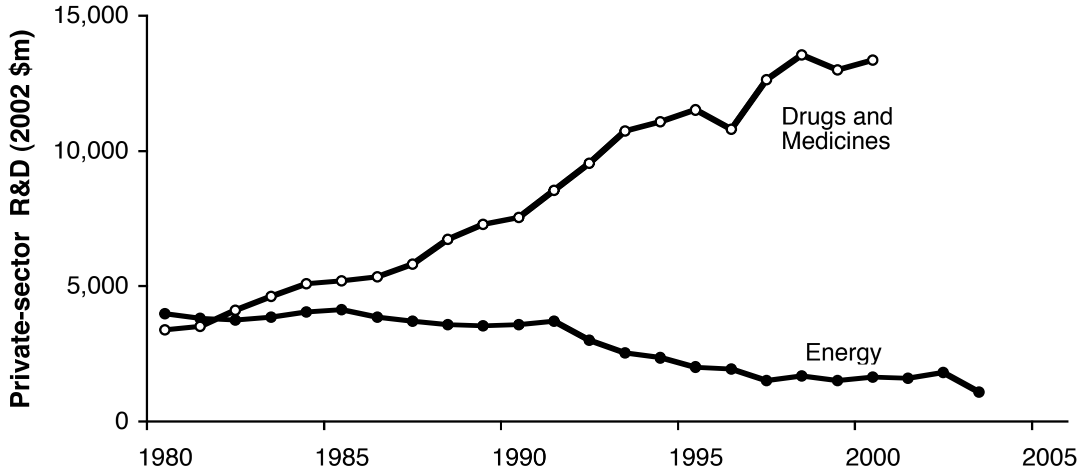

Figure 5 Private-sector R&D investment: energy vs. drugs and medicines

Addressing the Committee's questions

I now address specific questions posed by the Committee.

To what extent will the draft strategic plan meet the Administration's goal of reducing U.S. greenhouse gas emission intensity (the amount of emissions per unit of production) by 18 percent by the year 2012?

In responding to this question, it is important to make clear how *small* a change is necessary for the nation to meet the Administration's GHG intensity goal for 2012. In Figure 6 we compare the President's climate change goal to the business-as-usual reference case established by the EIA. In order to achieve the President's goal, a reduction of 3.6%, or 66 million tons of carbon equivalent, would be required below the BAU projection. To put this amount in perspective, this change could be accomplished by switching about 100 of our nation's 1500 coal burning power plants to natural gas. New technology would make such a switch easier. But we could accomplish such a change with no research program at all with a relatively modest change in only one sector. If an array of changes were implemented throughout the energy sector, to include end-use and transportation, meeting the carbon intensity goal would be even easier. Meeting other goals such as the Kyoto Protocol or stabilization at levels of 450 or 550ppm would require much larger changes, including widespread deployment of technologies described in the Strategic Plan.

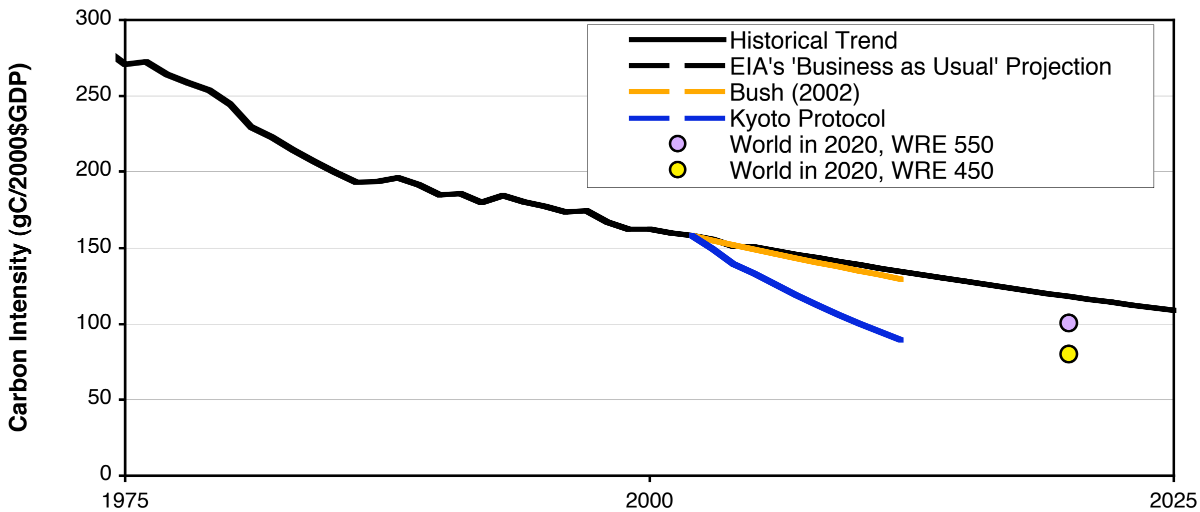

Figure 6 Carbon Intensity of the US Economy: Historical trend since 1975 and projection to 2025, with selected scenarios

Figure shows the carbon intensity of the US economy (in gC-equivalent/2000$GDP). The historical trend is shown from 1975 to 2002, with the EIA's "business as usual' (BAU) projection to 2025. Also shown are is the President's 2002 goal of an 18% reduction in carbon intensity below the 2002 level by 2012 and the Kyoto Protocol's goal of a

7% reduction in carbon emissions below 1990 levels by 2012. Additionally, the world "WRE stabilization pathways," named for the authors of a paper in Nature that has become a frequently used basis for carbon stabilization concentrations (see references), are used to calculate projected world average carbon intensity in 2020 for the 450 ppmv and 550 ppmv stabilization levels. In order to achieve Bush's goal, a reduction of 3.6%, or 66 million tons of carbon equivalent, would be required below the BAU projection. By contrast, in order to achieve the Kyoto Protocol's goal, a reduction of 33%, or 613 million tons of carbon equivalent, would be required. Note also that the WRE projections are world averages, which means that if enough other countries had carbon intensities higher than these values, it is possible that the US would have to reduce carbon intensity to below these values.

Does the Administration's strategic plan provide clear, unambiguous resource allocation guidance for the government's climate change technology R&D portfolio?

The plan's description of each technology program, including each program's overall strategy, current status, and future directions, does provide insight into the where resources will need to be allocated in order to bring programs toward commercially viable products. The broad array of technological options is an impressive feature of the plan. However, it is difficult to reconcile this rich and diverse technology portfolio with the budget summary in Appendix A.3. First, the plan does not clearly and unambiguously describe how each of the dozens of technology programs are to be funded. The budgets are listed at the level of the funding agency which gives little direction, for example, as to how much should be invested in biofuels versus carbon capture and sequestration. Second, it is difficult to imagine how a budget of slightly over three billion dollars per year can be used to fund the array of activities described in the plan at more than a trivial level. Real progress in programs such as fusion facilities and demonstrations of geological storage will require construction of facilities that will range in the tens to hundreds of millions of dollars. Funding a wide array of programs at relatively equal levels will ensure that these levels are low. A real danger exists that this funding will remain below critical thresholds for mobilizing needed technological improvements. If there is a prioritization of the programs that will allocate significant funds to a few key areas, it is not evident in the current public draft of the plan. Finally, a troubling omission is that the plan contains no budgets beyond 2006. This extremely short timeline for the budgets contained in the plan lies in stark contrast to the well-specified descriptions at the beginning of the document about the long term nature of the problem and the time it will take to develop the technological solutions to address it. The lack of clarity here is especially damaging because the absence of a longer term commitment sends an unnecessarily ambiguous signal to the private sector dampening the effect of the virtuous cycle that can emerge from government investment in R&D and subsequent investment by the private sectror.

Does the draft strategic plan appropriately balance the research needs that will enable the country to take short-, medium- and long-term actions to limit our greenhouse gas emissions and to adapt to any anticipated effects of climate change?

The strategic plan makes good use of emissions scenarios in its treatment of technology timing. On page 3-28, the plan makes the crucial point that the slow turnover of capital stock in the energy sector implies that technologies that need to achieve widespread deployment by midcentury will need to reach commercial readiness well before that, maybe even decades earlier. This infrastructural inertia combined with natural lags in the flows of GHG in the ocean, atmosphere, and biosphere creates an urgency that belies the long-time scales involved in the climate problem.

The “roadmap” in Figure 10-1 is a helpful visualization of the staged deployment of technology programs within the plan. Perhaps the most important text in Chapter 10 is the phrase “significant deployment.” Offsetting GHG emissions with new technologies requires widespread deployment of low and zero-carbon technologies. This need for broad adoption of the technologies at issue really brings into question the adequacy of our near term response to the problem. For example, achieving widespread deployment of hydrogen fuel cell automobiles in the 2025 to 2045 period, as the plan recommends, means that a significant number of those vehicles would need to begin entering the market ten years from today when a viable hydrogen fueling infrastructure would need to be in place. Significant deployment by 2035 means almost all new vehicles would need to be fuel cell vehicles by 2025, which implies that a large number of commercially available models would be available by 2015. Yet the plan’s goal for 2015 is merely to achieve reliability and cost targets in demonstration projects.

The roadmap is a succinct outline of the sequencing of the technology programs. What is missing is a clearer path for how these technologies emerge from modestly funded research programs, to demonstration, to early commercial applications, to rapid adoption, to the end goal, which is widespread deployment. As an example of what such a path might look lie, my students and I have produced a detailed analysis that shows how we can “decarbonize” the vehicles and electricity sectors through a small set of specific policies. We provide these illustrative scenarios in Appendix D, and note that work underway place in the Energy and Environment Division at Lawrence Livermore National Laboratory under the leadership of Dr. Jane Long is coming to similar conclusions.

Two important considerations: incentives for high-payoff research and commercialization

I would like to emphasize two additional important aspects of a substantially enhanced climate technology program. First, special emphasis may be needed to create incentives for high risk, high payoff research. We refer to a section within a recent National Academies report on this topic. And second, development efforts to hasten commercialization need to be included as well so that research programs acknowledge the need for demand-side incentives too.

This past fall, the National Academy of Science released an important report that raised the issue of American technological competitiveness and provided recommendations for improving the country’s capacity for innovation (Augustine, 2005). That report focused on the two fundamental issues that, in the opinion of its panel of experts, challenge our country's technical competence:

- Creating high quality jobs for Americans, and
- The need for clean, affordable, and reliable energy.

Setting energy-related challenges at the top of our country’s science and technology agenda is an important step and fits well with the situation outlined in the rest of this testimony. The recommendations in this study are admirable for their breadth including suggestions for K-12 education, basic research, university training, and incentives for innovation. Of particular interest to this committee is the panel's vision of a Defense Advanced Research Projects Agency (DARPA) for energy, "ARPA-E." Such a program would fund "high-risk research to meet the nation's long-term energy challenges" including universities, existing firms, and start-up ventures. The flexibility and independence of the DARPA model are key attributes that such a program seeks to emulate. Establishing an adequately funded organization like this would be a powerful commitment to securing our nation's energy future much as the way DARPA has done for our military power.

Important details to consider in setting up such an agency include ensuring that the demand-side of the problem is addressed as well. The military is unique in that the technologies being developed are created for a single customer under public sector control. Decision-making and technology adoption in the energy sector are much more dispersed and are deeply impacted by market forces as well as regulation. As a result, an ARPA-E program would need to be more cognizant of the demand-side of the innovation process in order to bring high-risk, high-payoff energy technologies to widespread adoption. This may include more emphasis on collaboration and technology transfer activity between the government and the private sector. Prior work on federal energy R&D, such as the PCAST studies (PCAST, 1997, 1999), has emphasized the importance of designing programs and policies that provide pathways for technologies that emerge from R&D programs to find full-scale commercial applications. The notion of the "valley of death" is based on the observation that technologies that succeed in proceeding from research to development to demonstration face important new obstacles in becoming viable commercial products. Technologies at this stage are often one-of-a-kind demonstrations and have not been built at full scale, large volume manufacturing problems need to be solved, and reliability must be demonstrated to skeptical customers. Past experience shows that technological success is not sufficient to bring new energy technologies to market. The challenges of scaling up, investing in manufacturing and distribution, building institutional capacity, and customer education need to be addressed as well. Past energy R&D programs may have put too little emphasis on this critical stage and a large new initiative needs to address these issues as well if the United States is to take full advantage of the benefits that emerge from the research programs. For example, public funding may need to be allocated for demonstration projects that stimulate learning effects, prove the viability of unfamiliar technologies, and mediate the risks to early adopters.

Common misconceptions about an aggressive energy R&D program

Some have expressed skepticism about the need for a national program for high-payoff energy R&D. Here I'd like to point out important misconceptions behind five criticisms of such a program:

1. "*Energy research is already well funded by private firms.*" Our figures shown above show that this is clearly *not* the case, as R&D investment by private firms has fallen by 50% in the past decade and R&D intensity by energy firms is a factor of 10 below the U.S. average.

2. "*Public sector R&D will crowd-out private sector R&D*". For the economy as a whole, the evidence for this assertion is mixed at best (David et al., 2000). In the energy sector, there is so little private energy R&D that could be crowded out that this problem is small if it exists at all.

3. "*Venture capital will identify promising opportunities in the energy sector*". The emergence of VC investment in the energy sector has been encouraging. However, this is overwhelmingly for late-stage technologies with the potential for widespread adoption within 3 to 5 years.

4. "*Government programs would pick winners rather than let markets decide*". In early stage technologies, when uncertainty is high and risks are large, the best strategy is making a diverse set of uncorrelated investments. This strategy is best seen as placing multiple bets, not picking winners.

5. "*Emulating the success of DARPA for an ARPA-E program does not make sense because Department of Energy research programs are more productive than DARPA's*." It is extremely difficult to measure the productivity of the early stage research that DARPA funds. R&D productivity measures that focus on the direct and easy-to-measure benefits of new technologies, tend to underestimate the benefits of public R&D. For example, how would we assess the worthiness of DARPA's funding of research on semiconductors in the 1940s and 1950s and the internet in the 1970s?

Recommendations

- **Make Energy and the Environment a Core Area of Education in the United States.** Public interest and action on energy and environmental themes requires attention to make us 'eco-literate and economically savvy.' We must develop in both K-12 and college education a core of instruction in the linkages between energy and both our social and natural environment. The Upward Bound Math-Science Program and the Summer Science Program each serve as highly successful models that could be adapted to the theme of energy for a sustainable society at all educational levels. The launch of Sputnik in 1957 mobilized U. S. science and technology to an unprecedented extent, and should serve as a lesson in how powerful a use-inspired drive to educate and innovate can become. The Spring 2005 Yale Environment Survey found overwhelming interest in energy and environmental sustainability. Contrast that interest with the results of the Third International Mathematics and Science Study (TIMSS) where American secondary school students ranked 19th out of 21 countries surveyed in both math and science general knowledge. The United States can and should reverse this trend, and sustaining our natural heritage and greening the global energy system is the right place to begin.

- **Establish a Set of Energy Challenges Worthy of Federal Action.** Establish *SustainableEnergy USA* awards – modeled after the successful efforts of the Ashoka Innovators awards for social entrepreneurs and the Ansari X Prize initially given for space vehicle launch - that inspire and mobilize our remarkable resources of academia, industry, civil society, and government. These initiatives would support and encourage groups to take action on pressing challenges. An initial set of challenges include:

- Buildings that cleanly generate significant portions of their own energy needs ('zero energy buildings');

- Commercial production of 100 mile per gallon vehicles, as can be achieved today with prototype plug-in hybrids using a low-carbon generation technologies accessed over the power grid, or direct charging by renewably generated electricity, and efficient biofuel vehicles operating on ethanol derived from cellulosic feedstocks.

- Zero Energy Appliances (Appliances that generate their own power)

- 'Distributed Utilities'; challenges and milestones for utilities to act as markets for clean power generated at residences, businesses, and industries.

- **Make the Nation the Driver of Clean Vehicle Deployment.** As the Zero Emission Vehicle Mandate and the Pavley Bill (AB 1493) have shown in California, dramatic improvements in vehicle energy efficiency and reductions in carbon emissions are eminently achievable, given political leadership. A clear message, as well as dramatic carbon and financial savings, would come from a decision to only purchase for state transportation needs vehicles meeting a *high* energy efficiency target, such as 40 miles per gallon for sedans and 30 miles per gallon for utility vehicles. These standards are now possible thanks to improvements in vehicle efficiencies and the wider range of hybrids (including SUV models) now available. A key aspect of such a policy is to announce from the outset that the standards will rise over time, and to issue a challenge to industry that a partnership to meet these targets will benefit their bottom line and our nation.

- **Expand International Collaborations that Benefit Developing Nations at a Carbon Benefit.** The needs of many developing nations are focused on the challenges meet fundamental economic and environment goals for their people. At the same time, these are our goals as well, both as a nation that must lead the charge to a sustainable and equitable world, and as citizens of a world where we share the rights and responsibilities to protect the atmosphere. Greenhouse gases emitted anywhere impact us all, not only today but for decades to come. In many cases, tremendous opportunities exist to offset future greenhouse gas emissions and to protect local ecosystems both at *very* low cost, but also to directly address critical development needs such as sustainable fuel sources, the provision of affordable electricity, health, and clean water. My laboratory has recently detailed the local development, health, *and* the global carbon benefits of research programs and partnerships on improved stoves and forestry practices (Bailis, Ezzati, and Kammen, 2005) across Africa. Far from an isolated example, such opportunities exist everywhere, with the recent wave of interest in 'sustainability science' (Jacobson and Kammen, 2005) a resource, aid, and business opportunity that the U. S. should embrace.

- **Recognize and Reflect Economically the Value of Energy Investment to the Economy.** Clean energy production – through investments in energy efficiency and renewable energy generation – has been shown to be a winner in terms of spurring innovation and job creation. This should be reflected in federal economic assessments of energy and infrastructure investment. Grants to states, particularly those taking the lead on clean energy systems, should be at heart of the federal role in fostering a new wave of 'cleantech' innovation in the energy sector.

- **Begin a Serious Federal Discussion of Market-Based Schemes to Make the Price of Carbon Emissions Reflect their Social Cost.** A carbon tax and a tradable permit program both provide simple, logical, and transparent methods to permit industries and households to reward clean energy systems and tax that which harms our economy and the environment. Cap and trade schemes have been used with great success in the US to reduce other pollutants and several northeastern states are experimenting with greenhouse gas emissions trading. Taxing carbon emissions to compensate for negative social and environmental impacts would offer the opportunity to simplify the national tax code while remaining, if so desired, essentially revenue neutral. A portion of the revenues from a carbon tax could also be used to offset any regressive aspects of the tax, for example by helping to compensate low-income individuals and communities reliant on jobs in fossil fuel extraction and production.

Acknowledgments
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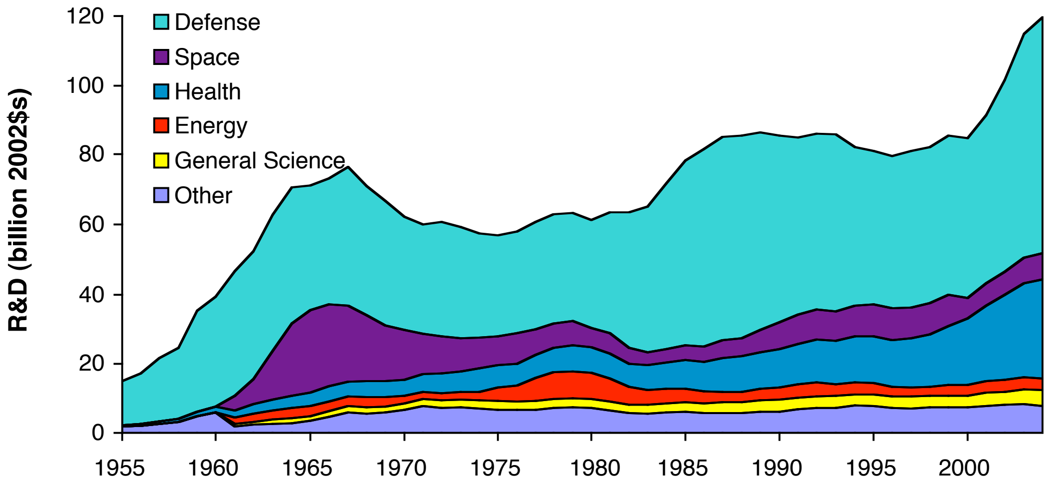
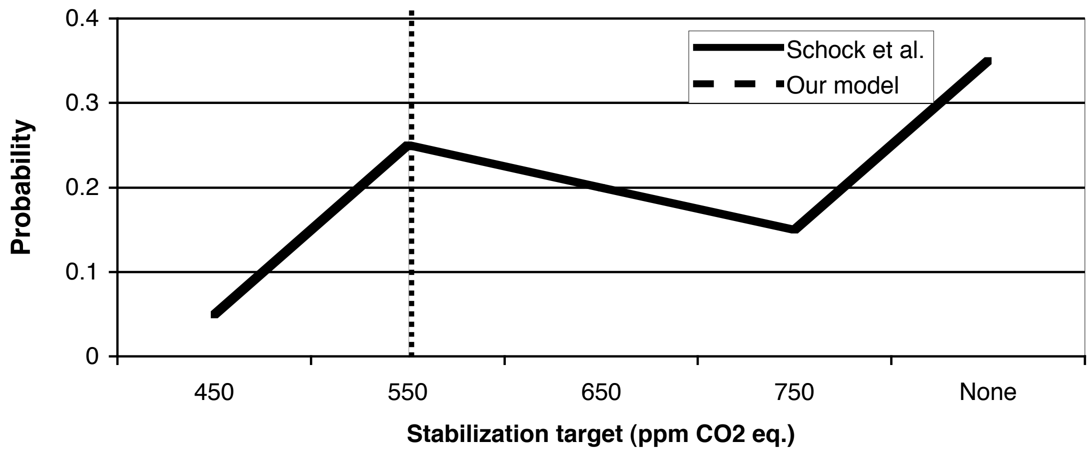
Appendix A: Previous federal R&D programs

This chart shows all U.S. federal R&D programs since 1955. Notice the thin strip showing how small the energy R&D program is relative to the others. The current budgets for energy R&D would continue this situation, or even reduce R&D investment (Kammen and Nemet, 2005)**.**



Appendix B: Estimating energy R&D investments required for climate stabilization

This note describes the methodology used to arrive at the estimates for future energy R&D in Kammen and Nemet (2005). Schock et al. (1999) valued energy R&D by providing estimates of the insurance needed against oil price shocks, electricity supply disruptions, local air pollution, and climate change. By estimating the magnitude of the risks in each area and the probabilities of energy R&D programs to reduce them, they found that increasing energy R&D by a factor of four would be a 'conservative' estimate of its insurance value. We note that this estimate assumes a mean climate stabilization target of between 650 and 750 ppm CO_2 equivalent and incorporates a 35% probability that no stabilization at all will be needed. This possibility of no stabilization at all is especially concerning as it would potentially involve levels exceeding 1000 ppm CO_2 by the end of the century, with higher levels thereafter.



Probability density function for climate stabilization used by Schock *et al.* compared with the 550 ppm target used in Kammen and Nemet (2005).

A recalculation of their model to target the 550-ppm atmospheric level, scenario A1T ('rapid technological change') of the Intergovernmental Panel on Climate Change (Nakicenovic, Alcamo et al. 2000), increases the optimal R&D investment in energy R&D to \$11 to \$32 billion, 3 to 10 times the current level of investment.

Model Description

The model devised by Schock et al. establishes an "insurance value" of federal energy R&D. It is based on assessing risk mitigation due to R&D for four types of energy-related risks. The non-climate risks are discussed at the end of this appendix. The value of R&D for mitigating climate change is calculated according to the following:

The value of R&D for the U.S. (V_{US}) is the product of the climate mitigation savings derived from R&D programs (S), the assumed probability of R&D success (P), and the probability of needing to achieve each stabilization level (L). These values are summed for each stabilization level (i) and multiplied by the contribution to worldwide climate R&D by the U.S. (A).

$$V_{US} = A \sum_i (S_i P_i L_i)$$

Like Schock *et al*., we assume that the contribution to worldwide R&D by the U.S. (A) is in proportion to its current share of worldwide greenhouse gas emissions, approximately 25%.

The subscript i represents 5 greenhouse-gas stabilization levels: 450 ppm, 550 ppm, 650 ppm, 750 ppm, and the case of no stabilization.

The probabilities (L) of needing to stabilize at each level i, are used as shown in the figure above. For the Schock et al. model these are: 0.05 at 450 ppm, 0.25 at 550 ppm, 0.2 at 650 ppm, 0.15 at 750 ppm, and 0.35 for the case of no stabilization. In contrast to the probability density function used by Schock et al., we select the doubling of pre-industrial levels as our target and thus assign the level i = 550ppm a "probability" of 1.

We use the values developed by Schock et al. for the assumed probability of R&D success (P). These probabilities decrease with stabilization levels, under the assumption that lower stabilization will require larger contributions from early-stage technologies whose ultimate viability is less likely than near-term options. The range for 550 ppm is 0.5 to 0.8. We use both ends of this range to bound our estimate.

For each stabilization level i, the climate mitigation savings derived from R&D programs (S) is the difference between the costs to stabilize using the outcomes of a successful R&D program (CRD) and the costs to stabilize without the R&D program (C).

$$S_i = C_i - CRD_i$$

We use the costs to stabilize (C) calculated by Schock et al., who used the MiniCAM 2.0 model applied to two sets of mitigation scenarios, those by Wigley et al. (1996) and the IPCC. The cost to stabilize at 550 ppm is in the range of $0.9 to $2.4 trillion. It is important to note that these scenarios already include technology improvement, although they do not specify how much R&D is implied to achieve this "autonomous" improvement. As Schock *et al.* point out, if any of this assumed improvement depends on higher levels of R&D, the estimates calculated in this model will then underestimate the R&D required.

The costs to stabilize using the outcomes of a successful R&D program (CRD) are lower because the energy technologies developed in the R&D program can be used to offset greenhouse gas emissions at lower costs than using existing technologies. We use the assumption by Schock et al. that a successful R&D program will enable us to deploy technologies that produce energy at costs similar to business-as-usual costs while reducing emissions sufficient to stabilize at the 550 ppm level.

Data comparison

The table below shows the values used in the model. In our version of the model we use the same values as Schock et al. for the 550 ppm level. The one exception is the probabilities assumed for the needing to achieve each stabilization level (L). Our model is conditional on a stabilization target of 550 ppm, because we are deriving the amount of R&D required to achieve a specific target. In contrast, Schock et al. treat the stabilization level as an uncertain parameter with a known probability density function.

Parameter values used in the model

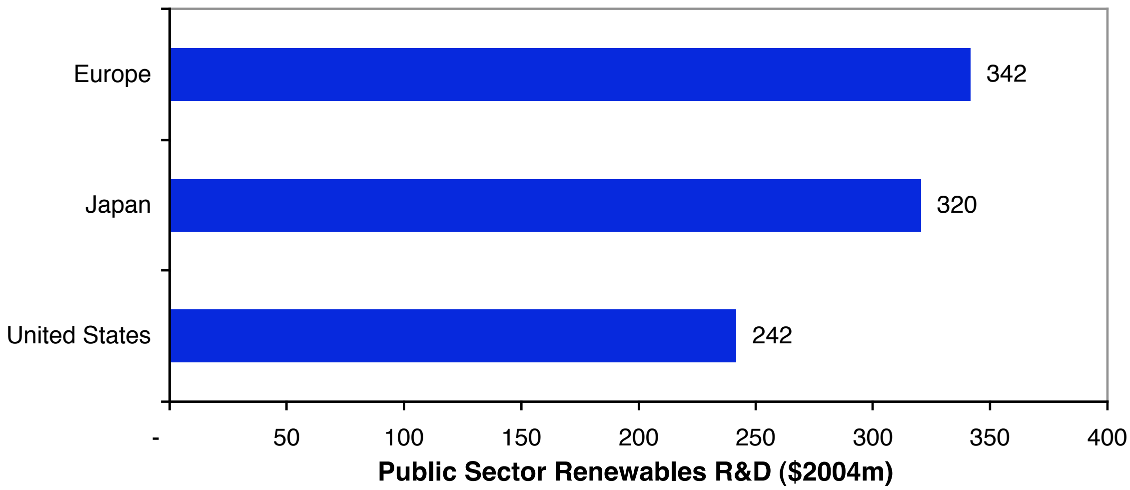
Study	Kammen and Nemet (2005)	Schock ***et al***. (1999)				
Stabilization level CO_2 (ppmv)	550	550	450	650	750	*None*
Cost to stabilize without R&D (C) $trillions	0.9 to 2.4	0.9 - 2.4	3.7 - 4.5	0.3- 1.3	0.2 - 0.5	0
Cost to stabilize with R&D (CRD) $trillions	0	0	0.4	0	0	0
Savings from R&D (S) $trillions	0.9 to 2.4	0.9 - 2.4	3.3 - 4.1	0.3 - 1.3	0.2 - 0.5	0
Probability of R&D success (P)	0.5 to 0.8	0.5 - 0.8	0.1	1.0	1.0	--
Probability of needing to achieve stabilization level (L)	1.0	0.25	0.05	0.2	0.15	0.35
U.S. share of worldwide R&D (A)	0.25	0.25				
Discount rate	0.05	0.05				

Outcomes

In our model, the total required spending was discounted and annualized to arrive at estimates for the required amount of annual federal energy R&D to stabilize atmospheric concentrations of CO_2 at 550 ppm. We arrive at a range of $6 to $27 billion in 2005 dollars.

Finally, we note that in their model, Schock et al. show energy R&D can be used as insurance against other risks as well, such as oil price shocks, electricity outages, and air pollution. Using energy R&D to mitigate these risks has an annual value estimated to be $9 to $10 billion. The figures above are if anything, overly conservative in that they assume that the R&D programs launched to address climate stabilization perfectly overlap with the programs used to address these other risks. A less conservative estimate would be to assume that perhaps half of the other risks would be addressed by the climate R&D program and half would not. For example, investments to improve the reliability of the electricity grid would reduce damages due to power outages but would not necessarily be included in a large climate R&D program. In that case, optimal energy R&D would rise to $11 to $32 billion per year, or roughly 3 to 10 times current levels. In our paper, we use scenarios of increases of factors of 5 and 10 to compare this range to the large R&D programs of the past.

Appendix C: Investments in renewables R&D across countries.



Investments in Renewable Energy Research and Development by OECD countries in 2004 (Data: Kammen and Nemet, 2005; International Energy Agency, 2005).

Appendix D: Achieving a low-carbon economy

By committing to a program of feasible carbon reductions in electricity and transportation sectors, we find that emissions can be reduced by up to 75% from today's levels.

At the current rate of demand increase, the electricity market has and will likely continue to grow at an annualized rate of 1.5%. With current electricity use estimated at 4000 terawatt-hours (TWh) per year, it is poised to increase to 5500 TWh/yr by 2025 and 7500 TWh/yr by 2050. Today, the net carbon emissions from different fossil fuel sources is about 2400 million metric ton carbon equivalents (MMTCE) per year and is projected to go up to 3700 MMTCE by 2025 and 5100 MMTCE by 2050.

We examine alternative scenarios of supply and demand in the electricity market between now and the year 2050 (Figure 1). Deployment of efficiency along with the growth of renewables are examined for their impact on electricity consumption and greenhouse gas emissions (Table 1).

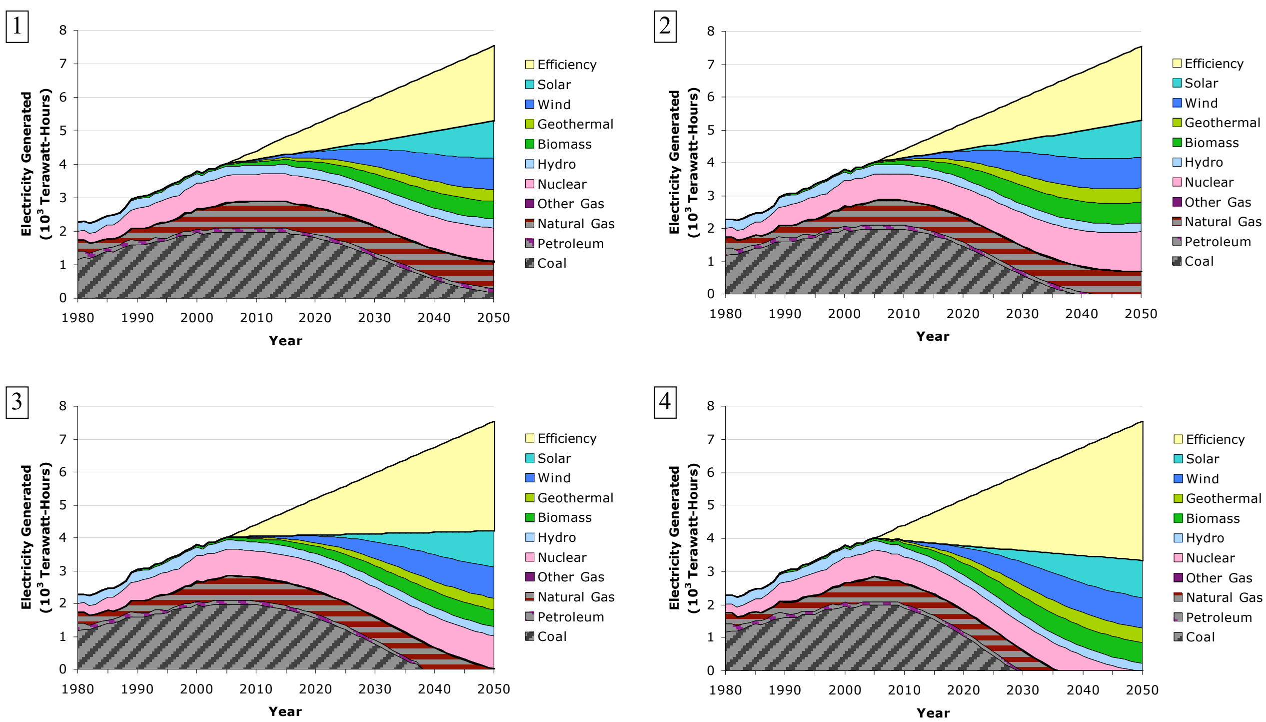


Figure 2. Alternative scenarios in the electricity market.

	Business-As-Usual	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Strategy	1.5% annual increase	1.0% Efficiency, Moderate	1.0% Efficiency, Aggressive	1.5% Efficiency, Moderate	2.0% Efficiency, Aggressive

		Renewables, Moderate Nuclear	Renewables, Aggressive Nuclear	Renewables, Moderate Nuclear	Renewables, No Nuclear
Electricity Consumed	7500 TWh	5300 TWh	5300 TWh	4200 TWh	3400 TWh
Carbon Emissions	5100 MMTCE	747 MMTCE	411 MMTCE	9 MMTCE	0 MMTCE
RPS [a]	5%	60%	64%	76%	100%

[a] Renewable Portfolio Standard (hydro, wind, solar, geothermal, and biomass)

Table 1. Description of scenario strategies and key findings for 2050 in the US electricity market.

The US currently uses 17 quads of primary energy for light duty fleet transportation. This figure is expected to grow to 24 quads in 2025 and 39 quads in 2050 under the current projected growth rate of 1.9% per year. Present emissions from light duty fleet transportation are 1,560 MMTCE and are projected to grow to 2,229 MMTCE by 2025 and 3,604 MMTCE by 2050. We examined potential reductions in CO_2 emissions from a business-as-usual approach by improving CAFÉ standards, increasing the market share of hybrid vehicles and meeting a larger portion of fuel demands with ethanol. We analyzed four scenarios based on moderate or aggressive paths of CAFÉ increases, hybrid market share increases and ethanol market share increases (Table 2).

Scenario	Description
BAU	BAU
Scenario 1	Moderate CAFE Moderate Hybrids Moderate Ethanol
Scenario 2	Moderate CAFE Aggressive Hybrids Aggressive Ethanol
Scenario 3	Aggressive CAFE Aggressive Hybrids Moderate Ethanol
Scenario 4	Aggressive CAFE Aggressive Hybrids Aggressive Ethanol

Table 2. Scenarios examined.

By 2025, light duty fleet carbon emissions can be reduced by approximately 29-45% from BAU and by 2050, carbon emissions can be reduced by approximately 58-72%.

	2025		2050	
	CO_2 Emissions	% Reduction from BAU	CO_2 Emissions	% Reduction from BAU
Strategy	**MMTCE**	**%**	**MMTCE**	**%**
BAU	2,229	-	3,604	-
Scenario 1	1,571	29.51	1,514	58.00
Scenario 2	1,508	32.34	1,242	65.54
Scenario 3	1,238	44.44	1,116	69.04
Scenario 4	1,218	45.36	1,010	71.98

Table 3. Potential reductions in light duty fleet CO_2 emissions.

Substantial savings from both the electricity and light vehicle sectors, which combined account for 65% of US emissions today, can be realized through a set of scenarios in both of these sectors (Figure 2). Nearly 75% from today's 4000 MMTCE can be saved under the most aggressive scenario.

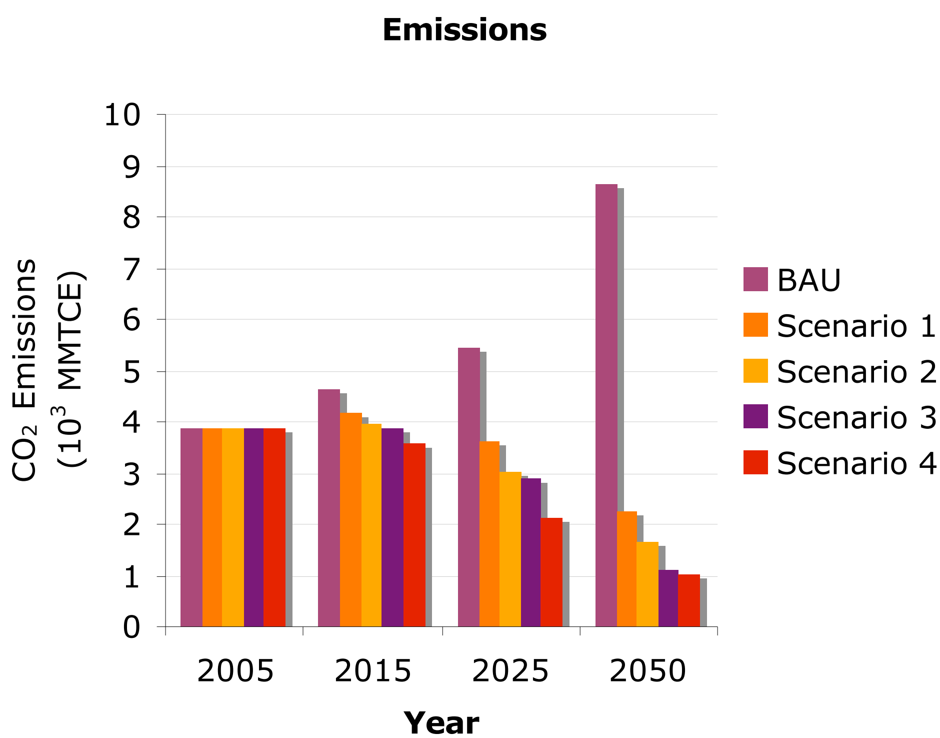


Figure 2. Carbon emissions from combined electricity and transportation sectors.

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