THE HAMILTON PROJECT

Advancing Opportunity, Prosperity and Growth

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Richard G. Newell

A U.S. Innovation Strategy for Climate Change Mitigation

THE BROOKINGS INSTITUTION

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A U.S. Innovation Strategy for Climate Change Mitigation

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Abstract

Within a market-based economy, success is maximized if policies directly address specific market problems. For technology innovation relevant to mitigating greenhouse gases (GHGs), the two principal market problems are a lack of private incentive to reduce GHGs by adopting low-GHG technologies, and underinvestment by industry in research and development (R&D), especially basic research. The strategy thus has two main parts to directly confront these two market problems, thereby increasing both the demand for and the supply of GHG-reducing innovations: (1) inducing innovation in industry through a stable, long-term price on GHGs, reinforced by permanent R&D tax credits, and (2) complementing this innovation through increased public support for targeted climate mitigation research in universities, other research institutions, and in the private sector.

The innovation strategy specifically recommends gradually increasing federal spending for climate mitigation research to roughly $8 billion per year over the next eight years, or roughly doubling energy research from 2007 levels by 2016. This increased funding should prioritize strategic basic research inspired by critical needs arising from efforts to develop new and improved GHG mitigation technologies, and should invest in training the next generation of scientists and engineers. Increased resources need to be tied to an effective management and coordination strategy for research focused on climate mitigation technology to ensure these funds are employed efficiently. Finally, a portion of these funds should be targeted to inducement prizes that provide financial rewards for achieving significant advances in climate mitigation innovation. In doing so, these funds would engage a broad set of innovators.

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1. Introduction

1.1. Overview of the Problem

To meet the greenhouse gas (GHG) emissions targets in U.S. legislative proposals will require large-scale adoption and innovation of GHG-reducing technologies throughout the U.S. economy, including technologies for increased energy efficiency, renewable energy, nuclear power, and carbon dioxide (CO_2) capture and storage. Meeting commonly discussed goals for stabilizing GHGs in the atmosphere will require similar technological changes across the global energy system, moving it dramatically away from a reliance on fossil fuels that is currently at more than 80 percent. While the importance of new technology in solving the climate problem is widely understood, there is considerable debate about what specific public policies and programs are necessary to bring about these technological changes as effectively and efficiently as possible. The potential economic payoff from well-designed policies is high, with potential U.S. mitigation costs through 2050 being on the order of \$1 to \$10 trillion (< 1 to 3 percent) of discounted gross domestic product (GDP), or an annualized \$50 billion–\$500 billion per year. Advanced technology holds the potential to significantly lower costs and expand options for GHG mitigation.

1.2. Overview of the Innovation Strategy

The innovation strategy is based on the simple principle that, within a market-based economy, success is maximized if policies directly address specific market problems. By directly addressing those problems, the policies should be designed to harness the power of private sector incentives for societal gain, and the direct governmental research role should be designed to complement rather than substitute for activities commonly undertaken by industry.

In the context of GHG-relevant technology innovation, there are two principal market problems (Goulder 2004; Jaffe, Newell, and Stavins 2005; Newell 2007a). First and foremost, there is the environmental externality of global climate change. If firms and households do not have to pay for the climate damage imposed by GHG emissions, then these emissions will be too high. This has implications for technology innovation and adoption because, if there is no demand for GHG reductions, then the demand for GHG-reducing technologies will also be too low. In turn, there will be insufficient incentive for companies to invest in mitigation technology R&D, because there will be little market demand for any innovations that might come of it.[1] A market-based emissions policy that places a price on GHGs—through either a cap-and-trade system or an emissions tax—is widely accepted to be a cost-effective response to this problem.

Second, there are problems specific to the market for innovations—not just with respect to climate, but more broadly. Knowledge, just like a stable climate, is a public good; it is well known individual companies cannot capture the full value of investing in innovation. That value tends to spill over to other technology producers and users, thereby diminishing individual private incentives for R&D; this problem tends to worsen the more basic and long term is the research. Therefore, well-targeted policy that boosts the level of innovation for climate mitigation technology has the potential to lower the overall cost of attaining long-term climate goals. The strategy thus has two main parts to directly confront these two market problems: (1) inducing innovation in industry through a price on GHGs,

1. For simplicity, the term *R&D* is intended to include initial “first-of-a-kind” demonstration projects focused on generating new knowledge.

reinforced by permanent R&D tax credits, and (2) complementing this innovation through increased public support for targeted research at universities, other research institutions, and in the private sector.

The first part of the innovation strategy seeks to harness the power of private sector investment. Industry performs 71 percent and funds 66 percent of total U.S. R&D, and is central to the U.S. innovation system. The single most important part of solving the climate technology problem is therefore to address the GHG externality through emissions pricing, giving the private sector a clear market signal of the returns to clean energy and other relevant innovations. This does not mean, however, that emissions pricing is the only important tool necessary to achieve climate mitigation goals. Science and technology policy to expand our options and reduce the future costs of mitigation has a valuable and important role to play, as long as it focuses on creating new knowledge. Encouraging increased private sector R&D by making the R&D tax credit permanent would bolster private incentives for innovation that would be induced by the emissions price, and would improve innovation incentives more generally.

While critical, more than three-fourths of industrial R&D is focused on development as opposed to basic and applied research. In contrast, universities, other nonprofits, and federal labs perform 85 percent of basic research, more than half (59 percent) of which is funded by the federal government (National Science Board 2008). These institutions play a complementary role to industry in the innovation system, so there is a need for policy that will supplement industrial R&D with more basic research relevant to lowering the cost of GHG mitigation and meeting other energy policy goals.

The second part of the climate innovation strategy is to gradually increase federal spending for climate mitigation R&D to roughly $8 billion per year (about $6.1 billion in real terms) over the next eight years, or roughly to double energy R&D from 2007 levels by 2016. This funding should place a priority on strategic basic research inspired by critical needs arising from efforts to develop new and improved GHG mitigation technologies. At the same time, this funding should invest in training the next generation of scientists and engineers. In order to encourage exploration of novel, emergent, or integrative concepts for addressing climate change, a program should also be established for exploratory research that pursues transformational technologies that may not fit well within existing basic or applied research programs. Increased resources need to be tied to an effective strategy for managing and coordinating climate mitigation technology research to ensure these funds are employed efficiently. Finally, a portion of these funds should be used to supplement the traditional research contracts and grants structure with inducement prizes that provide financial rewards for achieving significant advances in climate mitigation innovation. Prizes of this type can help focus research efforts on clearly defined objectives, instill a sense of urgency and competition, and engage a broad set of innovators.

Together, this strategy seeks to increase both the demand for and the supply of GHG-reducing innovations in a balanced way that emphasizes those aspects of the overall innovation process that the private and public components of the system are best oriented toward advancing. R&D push without the pull of demand is like pushing on a rope—ultimately doomed to failure. Market demand-pull without supportive R&D policies misses longer-term opportunities for significantly lowering GHG reduction costs and expanding opportunities for greater GHG mitigation. A coupled “emissions price plus R&D” strategy offers the best opportunity for mitigating GHG emissions at the lowest possible cost to society. Likewise, ratcheting up R&D and other technology policies in an attempt to compensate for insufficiently stringent emissions policy can dramatically raise the cost of achieving a given amount of GHG mitigation (Fischer and Newell 2008a, 2008b).

Note there are some aspects of climate technology policy that lie beyond the focus of this strategy. This includes the design of technology deployment policy, international climate technology policy, and programs related to the development of technologies for adaptation and direct climate modification. Although addressed to some degree here, for a more complete review of the role and design of technology deployment policies, see Newell (2007b); for a discussion of international climate technology strategies, see de Coninck et al. (2008) and Newell (2008).[2]

1.3. Roadmap

The next section (§2) lays out the technology challenge for climate change mitigation, describing current conditions and trends in GHG emissions and energy technologies, likely effects of projected GHG emissions on the global climate, the economic scale of the mitigation challenge, and the importance of advanced technology for lowering associated costs and expanding options. Section 3 highlights the key market problems relevant to GHG technology innovation, reviews current patterns and trends in private and public R&D, and identifies the highest priority areas for public policy in relation to private sector action.

In §4, I describe the part of the innovation strategy focused on inducing private sector innovation through a market-based price on GHG emissions, reinforced by permanent R&D tax credits. In §5, I turn to the part of the innovation strategy focused on complementing private innovation through expansion of federal funding for climate mitigation research, including an effective management strategy and the use of innovation inducement prizes. The final section (§6) concludes the paper.

2. Newell (2008) considers opportunities for improved and expanded international development and transfer of climate technologies. That paper clarifies the importance of options for inducing technology market demand through domestic GHG pricing, international trade, and international development assistance. It then turns to upstream innovation strategies, including international coordination and funding of climate technology R&D, and knowledge transfer through intellectual property. Newell (2008) concludes that a successful international effort to accelerate and then sustain the rate of development and transfer of GHG mitigation technologies must harness a diverse set of markets and institutions beyond those explicitly related to climate, to include those for energy, trade, development, and intellectual property.

2. The Technology Challenge for Climate Change Mitigation

Since it was adopted in 1992, the United Nations Framework Convention on Climate Change (UNFCCC) has been ratified by virtually all the world's 190-plus countries, including the United States. The treaty's principal objective, as stated in Article 2, is "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (United Nations 1992, 4). Although there is much debate about what level of GHG concentrations "would prevent dangerous anthropogenic interference," one thing is clear—stabilizing GHG concentrations *at any level* eventually implies reducing net GHG emissions to near zero.[3]

2.1. The Energy Technology Mix and GHG Emissions: Current Conditions and Trends

While the idea of balancing the atmospheric GHG stock by reducing the net GHG flow to zero is simple enough, the technological reality of what it will take to do this is far from simple. The current reality is that 84 percent of U.S. GHG emissions come from fossil fuels such as oil, coal, and natural gas, which satisfy 85 percent of U.S. energy consumption (U.S. Energy Information Administration [EIA] 2008a).[4] The remainder of U.S. energy consumption is supplied by nuclear power (8 percent) and renewable energy (7 percent), such as biomass, hydroelectric power, geothermal, wind, and solar power. Global statistics are similar: about 81 percent of world energy supply comes from fossil fuels, 6 percent from nuclear, and 13 percent from renewable sources (International Energy Agency [IEA] 2007b).

Stabilizing GHG concentrations therefore requires large-scale and widespread substitution toward energy technologies with low to zero net GHG emissions throughout the U.S. and global energy systems. Unfortunately, this is not the direction in which we have been heading. Given existing policies and expected market trends, the EIA "reference case" forecast has U.S. energy consumption increasing 19 percent and CO_2 emissions by 16 percent by 2030 over current levels, with a continued dominance of fossil fuels in the energy mix (80 percent fossil fuels, 8 percent nuclear power, and 12 percent from renewables in 2030; EIA 2008b).[5] While U.S. biofuel use is forecast to increase—due in large part to the renewable fuels provisions of the Energy Independence and Security Act of 2007—so is the share of coal, from 23 percent up to 25 percent of total U.S. energy consumption.

Global forecasts are equally—if not more—at odds with a vision of a future energy technology system having declining GHG emissions. The IEA reference case forecast is that world energy consumption will grow 55 percent and energy-related CO_2 emissions a whopping 57 percent between 2005 and 2030, with the fossil fuel share actually *rising* slightly from 81 to 82 percent (IEA 2007b). Over a longer timeframe, modelers of the integrated energy-economic-climate system typically estimate that—without additional policy actions—annual CO_2 emissions will increase by a factor of about two

3. Some nonzero level of continued GHG emissions is consistent with stabilizing atmospheric GHG concentrations since those emissions are eventually removed from the atmosphere and deposited in the deep ocean through the carbon cycle.
4. U.S. fossil fuel–related GHG emissions are 81 percent from carbon dioxide (CO_2), and 3 percent collectively from methane (CH_4) and nitrous oxide (N_2O) (EPA 2008b).
5. The term *reference case* is used to refer to a scenario that typically assumes no GHG mitigation (or other energy) policy is applied beyond what has already been adopted. This is also often called a *baseline scenario*. The term *business as usual* is often used interchangeably, but I avoid this term because the market and technological changes embodied in these reference case projections imply significant changes relative to current conditions.

in the United States and three globally by the end of this century (Clarke et al. 2007; Fisher et al. 2007; Weyant, de la Chesnaye, and Blanford 2006).[6]

These and other forecasts serve to underscore what is by now perhaps painfully obvious—the energy-economic system has a tremendous predilection toward fossil fuel–based technologies and is not going to right itself with respect to the global climate absent substantial public policies that encourage it to do so. The simple reason is that, given the existing suite of technological options, fossil fuels have tended to be a more reliable source of large quantities of relatively inexpensive energy compared to more climate-friendly alternatives. This continues to be the case even with recent increases in oil, natural gas, and coal prices. In economic terms, GHG emissions by anyone impose an environmental externality cost on everyone, yet this cost goes unpaid and emissions remain too high unless policy is in place to put a price on GHGs.

2.2. Climate Change Science and the Likely Effects of Increased GHG Concentrations

At the same time that the scale of these projections of energy use and GHG emissions has been sinking in, there has been increased clarity of the science underpinning human-caused global warming and the potential impacts thereof. As a result, the momentum for international commitments and national-level policies requiring mandatory GHG emissions reductions has intensified significantly. In that context, much discussion has surrounded targets for stabilizing CO_2 concentrations in the atmosphere at 550 parts per million of CO_2 (ppm CO_2) or lower, where 550 ppm CO_2 represents roughly a doubling of CO_2 concentrations relative to preindustrial levels of 280 ppm CO_2; the current level is 380 ppm CO_2 (Intergovernmental Panel on Climate Change [IPCC] 2007). Other major GHGs contribute approximately 70 ppm CO_2 equivalent (CO_2e)[7] to present GHG concentrations, bringing the current concentration of the six main GHGs in the atmosphere to about 450 ppm CO_2e (IPCC 2007).[8]

Figure 1 shows the range of long-term warming expected at different GHG stabilization levels based on recent IPCC estimates of the climate sensitivity—that is, the likely temperature response to a change in atmospheric GHG concentrations. The IPCC Fourth Assessment Report (IPCC 2007, 38) states that

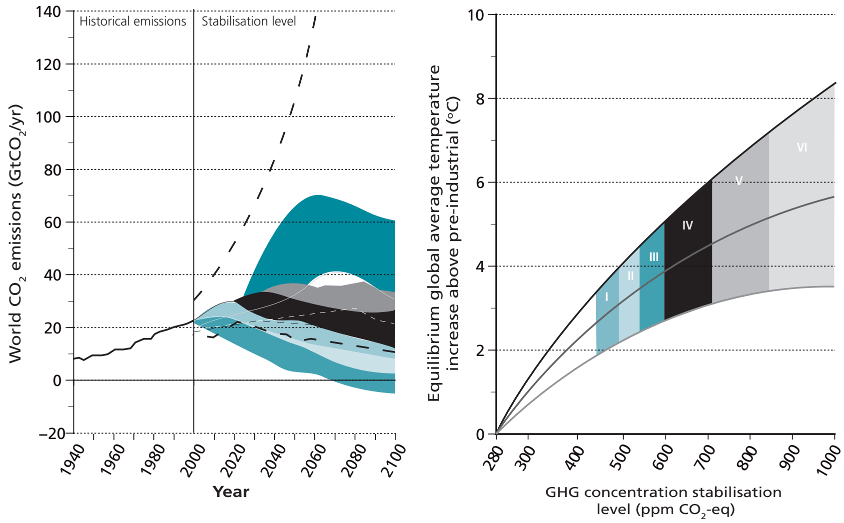
> The equilibrium climate sensitivity is a measure of the climate system response to sustained radiative forcing. It is defined as the equilibrium global average surface warming following a doubling of CO_2 concentration. …[C]limate sensitivity is *likely* to be in the range of 2°C to 4.5°C with a best estimate of about 3°C, and is *very unlikely* to be less than 1.5°C.

Note that changes in degrees Fahrenheit are roughly twice as large as changes in degrees Celsius (nine-fifths, to be exact). For each of the different GHG stabilization ranges given in CO_2e in Figure 1 (i.e., shaded categories I–VI), Figure 2 shows the associated CO_2 concentrations, the year that global GHG emissions must roughly peak in order to achieve these stabilization levels, the change in global emissions relative to year 2000, best estimate global average temperature increases, global average sea-level increases, and the number of model scenarios on which the estimates are based.

6. There is nonetheless a wide range of forecast emissions levels due to uncertainty in the main driving forces, such as population growth; economic development; and energy production, conversion, and end use (Fisher et al. 2007; Weyant 1993, 2000).
7. CO_2 equivalence is a means of measuring the total concentration of all GHGs, not solely CO_2. The six major GHGs identified in Annex A of the Kyoto Protocol to the UNFCCC are CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).
8. About 2–3 ppm CO_2e are currently added to the atmosphere each year, and this amount has been growing. Other anthropogenic activities (including aerosol emissions and land-use changes) have a net cooling effect (negative radiative forcing) such that the current net forcing effect from anthropogenic sources is approximately equal to 380 ppm CO_2e. Reducing these other activities would make the stabilization challenge more difficult.

FIGURE 1

CO_2 Emissions and Equilibrium Temperature Increases for a Range of GHG Stabilization Levels



Global CO_2 emissions for 1940 to 2000 and emissions ranges for categories of stabilisation scenarios from 2000 to 2100 (left-hand panel); and the corresponding relationship between the stabilisation target and the likely equilibrium global average temperature increase above pre-industrial (righthand panel). Approaching equilibrium can take several centuries, especially for scenarios with higher levels of stabilisation. Coloured shadings show stabilisation scenarios grouped according to different targets (stabilisation category I to VI). The right-hand panel shows ranges of global average temperature change above pre-industrial, using (i) 'best estimate' climate sensitivity of 3°C (line in middle of shaded area), (ii) upper bound of likely range of climate sensitivity of 4.5°C (line at top of shaded area) (iii) lower bound of likely range of climate sensitivity of 2°C (line at bottom of shaded area). Black dashed lines in the left panel give the emissions range of recent baseline scenarios published since the SRES (2000). Emissions ranges of the stabilisation scenarios comprise CO_2-only and multigas scenarios and correspond to the 10th to 90th percentile of the full scenario distribution. Note: CO_2 emissions in most models do not include emissions from decay of above ground biomass that remains after logging and deforestation, and from peat fires and drained peat soils. {WGIII Figures SPM.7 and SPM.8}

Source: IPCC 2007, Figure 5.1, p. 66.

FIGURE 2

Projected Emissions, Temperature Increase, and Sea-Level Rise for a Range of GHG Stabilization Levels

Category	CO_2 concentration at stabilisation (2005 = 379 ppm)[b]	CO_2-equivalent concentration at stabilisation including GHGs and aerosols (2005 = 375 ppm)[b]	Peaking year for CO_2 emissions [a,c]	Change in global CO_2 emissions in 2050 (percent of 2000 emissions)[a,c]	Global average temperature increase above pre-industrial at equilibrium, using 'best estimate' climate sensitivity[d,e]	Global average sea level above pre-industrial at equilibrium from thermal expansion only	Number of assessed scenarios
	ppm	ppm	year	percent	°C	metres	
I	350-400	445-490	2000-2015	-85 to -50	2.0-2.4	0.4-1.4	6
II	400-440	490-535	2000-2020	-60 to -30	2.4-2.8	0.5-1.7	18
III	440-485	535-590	2010-2030	-30 to +5	2.8-3.2	0.6-1.9	21
IV	485-570	590-710	2020-2060	+10 to +60	3.2-4.0	0.6-2.4	118
V	570-660	710-855	2050-2080	+25 to +85	4.0-4.9	0.8-2.9	9
VI	660-790	855-1130	2060-2090	+90 to +140	4.9-6.1	1.0-3.7	5

Notes:
a) The emission reductions to meet a particular stabilisation level reported in the mitigation studies assessed here might be underestimated due to missing carbon cycle feedbacks (see also Topic 2.3 in IPCC 2007).
b) Atmospheric CO_2 concentrations were 379ppm in 2005. The best estimate of total CO_2-eq concentration in 2005 for all long-lived GHGs is about 455ppm, while the corresponding value including the net effect of all anthropogenic forcing agents is 375ppm CO_2-eq.
c) Ranges correspond to the 15th to 85th percentile of the post-TAR scenario distribution. CO_2 emissions are shown so multi-gas scenarios can be compared with CO_2-only scenarios (see Figure 2.1 in IPCC 2007).
d) The best estimate of climate sensitivity is 3°C.
e) Note that global average temperature at equilibrium is different from expected global average temperature at the time of stabilisation of GHG concentrations due to the inertia of the climate system. For the majority of scenarios assessed, stabilisation of GHG concentrations occurs between 2100 and 2150 (see also Footnote 30 in IPCC 2007).
f) Equilibrium sea level rise is for the contribution from ocean thermal expansion only and does not reach equilibrium for at least many centuries. These values have been estimated using relatively simple climate models (one low-resolution AOGCM and several EMICs based on the best estimate of 3°C climate sensitivity) and do not include contributions from melting ice sheets, glaciers and ice caps. Long-term thermal expansion is projected to result in 0.2 to 0.6m per degree Celsius of global average warming above pre-industrial. (AOGCM refers to Atmosphere-Ocean General Circulation Model and EMICs to Earth System Models of Intermediate Complexity.)
Source: IPCC 2007, Table 5.1, p. 67.

To get a sense of what current trends imply, typical scenarios show reference case atmospheric concentrations in the range of 700–900 ppm CO_2 (900–1400 ppm CO_2e) by 2100, with continued increases beyond this timeframe (Clarke et al. 2007; Weyant, de la Chesnaye, and Blanford 2006). This is the far-right-hand side of Figure 1, or higher, with likely eventual global average temperature increases of about 4ºC–8.5°C (7ºF–15°F) at 1000 ppm CO_2e, relative to preindustrial levels. Projected temperature increases and associated impacts at the regional level vary over an even wider range. In contrast, stabilization at 550 ppm CO_2 (about 670 CO_2e) or less would significantly reduce the risk of the large temperature changes that are associated with current trends (Figures 1 and 2).

2.3. Economic Scale of the Mitigation Challenge: Emissions Targets and Projected Costs

In order to gauge, in economic terms, the magnitude of the innovation challenge presented by climate change, it is helpful to consider possible GHG emissions targets and the projected costs of achieving these targets. These projected costs, most commonly measured in terms of reduced GDP, indicate the scale of the payoff that could come from innovations that significantly reduce (or, in the extreme, eliminate) the cost disadvantage of climate-friendly technologies relative to the competition. If such low-cost alternatives also made it feasible and desirable to undertake more significant reductions than otherwise, then there would be an added benefit from the further climate damages that are avoided. While this paper focuses on GHG mitigation, there are additional benefits from lower-cost, climate-friendly innovations: in the form of increased energy security (e.g., decreased exposure to oil price shocks and national security risks); decreases in the control costs and increased abatement of conventional air pollutants (e.g., particulates, mercury, ground-level ozone); increases in product quality (e.g., better lighting); and expansion of technological possibilities in fields that draw on the same underlying advances.[9] Indeed, technologies that would underpin a transition to a climate-friendly energy system also tend to address energy security and oil dependency concerns. It is very difficult to quantify these types of innovation benefits even after they have occurred, however, never mind in advance.

The intention is not to suggest a particular target here, which is a complex societal decision that will no doubt evolve significantly over time. Rather, it is to consider a range of targets that is sufficient to give one a sense of the scale of the technical challenge, in economic terms, that is being considered by policymakers. At one end, the European Commission and others have adopted the explicit goal of limiting global warming to no more than 2°C above preindustrial levels, with an associated long-term GHG stabilization target of around 450 ppm CO_2e (European Commission 2007). Bills introduced in the 110th Congress by Senator Sanders (S. 309, Global Warming Pollution Reduction Act) and Senator Kerry (S. 485, Global Warming Reduction Act of 2007) mention the same goal. These targets are at the most stringent end of the spectrum indicated toward the left of Figure 1, and there are very few modeling results available to gauge the global mitigation cost of achieving GHG stabilization below about 530 CO_2e (i.e., 450 CO_2, or categories I and II in Figure 1). One reason is that achieving long-term stabilization at 450 ppm CO_2e will almost surely involve overshooting this target in the near term, given that current levels are already at 450 ppm CO_2e, not including aerosols that currently cool the planet.

At the other end of the spectrum is obviously doing nothing to mitigate GHG emissions. It is useful to consider this option, mainly to point out that the value of climate technology innovation is substantially reduced if there is no intention to reduce

9. See Schock et al. (1999) for an assessment of the value of energy research in terms of its insurance value against the risks of climate change, oil price shocks, urban air pollution, and other energy disruptions.

GHG emissions, although it is still unlikely to be zero due to co-benefits. However, this is an option that virtually all countries have rejected, as indicated by the 190-plus signatories to the UNFCCC. In any event, most policy proposals and certainly most analysis has centered on emissions paths that are consistent with ultimate stabilization targets in the range of 450–550 ppm CO_2. (This is as opposed to CO_2e; recall there is currently an additional 70 ppm of CO_2e of other GHGs in the atmosphere, which are also projected to increase along with CO_2.)

One source of recent estimates of the cost of stabilization in this range is the three models participating in the U.S. Climate Change Science Program stabilization scenarios study (Clarke et al. 2007).[10] Based on estimates from that study, the cost of stabilizing GHG concentrations at 550 ppm CO_2 (670 CO_2e) is in the range of \$3–\$30 trillion, or a 0.2–2 percent decrease in the present value of global GDP through 2100, depending on the model employed (Table 1).[11] The cost of a 450 ppm CO_2 (530 CO_2e) stabilization target is about three to five times as high in that study; about \$15–\$90 trillion or a 1–5 percent decrease in discounted global GDP. Costs through 2050 are about half the costs through 2100.

U.S.-specific GDP losses are not available in that study, but allocating 25 percent of the cost to the United States implies a present value cost to the United States (through 2050) of about \$0.1 trillion–\$3 trillion (<1 percent of GDP) for the 550 ppm CO2 target and \$2 trillion–\$11 trillion (1–3 percent of GDP) for the 450 ppm CO2 target.[12] Note that these and many other model-based cost estimates assume the GHG stabilization target is attained at minimum cost by flexibly reducing any of the six GHGs (not solely CO_2) in the country, year, and sector, using the technology that makes the most economic sense. In practice, real-world

TABLE 1

Range of Estimated Present Value Cost of GHG Stabilization
(units as indicated)

	2010–2050 decrease in present value GDP			2010–2100 decrease in present value GDP		
GHG stabilization target	Global percent decrease	Global (\$ trillions)	U.S. 25% "share" (\$ trillions)	Global percent decrease	Global (\$ trillions)	U.S. 25% "share" (\$ trillions)
450 CO_2 (530 CO_2e)	1–3	8–43	2–11	1–5	16–91	4–23
550 CO_2 (670 CO_2e)	0–1	0.4–12	0.1–3	0.2–2	3–30	0.7–7

Source: The estimates are based on results from three models that participated in the U.S. Climate Change Science Program GHG stabilization scenario study Clarke et al. 2007.
Note: Changes in GDP relative to the reference case scenario over the indicated period are discounted to 2010 at a 5 percent discount rate. U.S. GDP is an average of roughly 25 percent of global GDP in these scenarios.

10. The three models are (1) the Integrated Global Systems Model (IGSM) of the Massachusetts Institute of Technology's Joint Program on the Science and Policy of Global Change; (2) the Model for Evaluating the Regional and Global Effects (MERGE) of GHG reduction policies developed jointly at Stanford University and the Electric Power Research Institute; and (3) the MiniCAM Model of the Joint Global Change Research Institute, which is a partnership between the Pacific Northwest National Laboratory and the University of Maryland.
11. Estimates from the Stanford Energy Modeling Forum EMF21 assessment of a similar stabilization target found a similar range of costs across a larger number of models (Weyant et al. 2006).
12. The allocation of responsibility for the costs of global climate mitigation to individual countries is a complex issue ultimately subject to international negotiation and domestic action. Allocating one-fourth of such costs to the United States is based on the average U.S. share of global GDP in the assessment models references above. This share is also consistent with the U.S. percentage of a range of estimates of past cumulative global GHG emissions (Baumert et al. 2005).

policies and institutions are likely to make costs higher, although other assumptions in the models could of course implicitly overestimate the costs (Newell and Hall 2007).

Economic assessments of various climate bills pending in the U.S. Congress provide another lens on the projected cost of climate mitigation, and thus the value of R&D that potentially reduces these costs. Two bills that have had the most traction are the Lieberman-Warner Climate Security Act of 2008 (S. 2191) and the Low-Carbon Economy Act of 2007 (S. 1766, or the Bingaman-Specter bill). Both propose to establish a broad-based cap-and-trade system covering all six GHGs from electric power, transportation, and industrial sectors of the U.S. economy. S. 2191 targets a 70 percent reduction of covered emissions from 2005 levels by 2050 and S. 1766 targets a 60 percent reduction in GHG emissions below 2006 levels by 2050, although the specific targets in S. 1766 remain constant after 2030.[13] The aggregate amount of GHG emissions one might expect will actually be allowed by the specific provisions of the bills is likely to be somewhat less stringent than these targets in percentage terms, however, because not all emissions are covered and there are provisions that allow flexibility in the targets that one would expect will be used.

Based on RTI International's ADAGE model, the U.S. Environmental Protection Agency (EPA 2008a) estimates the cost of the Lieberman-Warner bill (S. 2191) would gradually increase over time to about a 2.4 percent decrease in U.S. GDP by 2050 relative to a reference case. The present value of this lost GDP (at a 5 percent discount rate) would be about \$4 trillion, or 1 percent of discounted GDP over the 2010–50 period. This is equivalent to a constant annualized cost of about \$220 billion per year. It is useful to note EPA also estimates that, with adoption of the Lieberman-Warner bill, global CO_2 concentrations at the end of the century would likely be about 500 ppm CO_2, assuming certain actions would be undertaken by other countries. Scenarios in the same EPA analysis found the costs of the policy in terms of reduced GDP roughly doubled if the use of nuclear, biomass, and carbon capture and storage (CCS) were to be constrained (EPA 2008a). In comparison, EPA-estimated costs are half the level for the Bingaman-Specter bill (S. 1766) as for the Lieberman-Warner bill (i.e., \$2 trillion in discounted GDP loss, 0.5 percent of discounted GDP, and about \$100 billion per year annualized for 2010–50). Analysis by Paltsev et al. (2007) of a range of U.S. cap-and-trade proposals found comparable costs for policies of similar stringency, with higher costs for more stringent policies and lower costs for more modest policies.

In summary, modeling scenarios of cost-effective global and U.S. domestic climate mitigation policy suggest the cost to the United States of GHG mitigation through 2050 could be on the order of \$1 trillion to \$10 trillion (<1 to 3 percent) of discounted GDP, or an annualized \$50 billion to \$500 billion per year, depending of course on the stringency of global and U.S. emissions targets, the share of the associated costs borne by the United States, and the specific design of policies implemented. Longer-term costs through 2100 to achieve GHG stabilization at between 450 and 550 ppm CO_2 are approximately double these amounts. While these estimates are subject to numerous economic and policy assumptions, they give a sense of the order of magnitude of the payoff to the United States of innovations that could significantly lower the cost of achieving various GHG reduction goals.

13. A White Paper from the U.S. House of Representatives Energy and Commerce Committee staff (2007) states, "A consensus is developing that the United States should reduce its greenhouse gas emissions by 60 to 80 percent by 2050 to contribute to global efforts to stabilize atmospheric greenhouse gas concentrations at a CO_2-equivalent level between 450 to 550 parts per million." This is consistent with the goal set out by the U.S. Climate Action Partnership (U.S. Climate Action Partnership [USCAP] 2007), a coalition of major U.S. companies and environmental organizations. USCAP's goal is that "Congress should specify an emissions target zone aimed at reducing emissions by 60% to 80% from current levels by 2050."

2.4. Importance of Advanced Technology for Lowering Costs and Expanding Options

Many studies have demonstrated the central role that the availability and cost of advanced energy technologies plays in determining the cost of achieving various GHG emissions targets.[14] These technical possibilities manifest themselves in two important ways in climate modeling: (1) through forecasts made about how energy technologies will develop and deploy in the absence of climate policy (that is, the reference case or baseline technology assumptions); and (2) through assumptions about how this technological process will (or will not) change once the economy is confronted with a particular emissions or technology policy.

To the first point, the reference case scenarios employed by virtually all the models used, including those cited above, already include significant technological advance that reduces the baseline level of GHG emissions as well as the cost of achieving reductions relative to that baseline.[15] While it is not typically made explicit in these models, there is presumably a significant degree of innovative effort in the form of R&D, learning, and diffusion of new technologies that would have to underpin these baseline technological improvements.

The future availability and cost of advanced energy technologies also plays a key role in determining the cost of achieving any given GHG emissions target. This degree of sensitivity of climate mitigation costs to technology development is well established, going back to early work by Manne and Richels (1992), who found the GDP costs of mitigation were approximately 90 percent lower globally in their optimistic technology scenario compared to their central case. A more recent study conducted by Clarke et al. (2006) explored several alternative advanced technology futures and compared the energy, emissions, and economic implications of achieving a number of different GHG stabilization scenarios. As in other studies, they found that no single technology or class of technologies is likely to provide the scope or quantity of GHG emissions mitigation needed to achieve stabilization at the levels examined. Rather, the cost-effective technology solution entails a mix of energy efficiency, low-GHG energy supply (including CCS), and emissions reductions in non-CO_2 GHGs. Thus, R&D supporting such a transition must also be broad-based, covering a wide range of technological opportunities.

Importantly, Clarke et al. (2006) found that accelerated technology development offers the potential to dramatically reduce the costs of stabilization, with their advanced technology scenarios reducing the cumulative costs of stabilization (present value through 2100) by 50 percent or more, yielding economic benefits of hundreds of billions to trillions of dollars globally (Figure 3). Edmonds et al. (2004) similarly found that in future scenarios where a set of advanced technologies (e.g., CCS, biotechnology, and hydrogen energy systems) are available, the cost of GHG mitigation was 60 percent lower than a case where these advancements were not available. While one might reasonably argue over detailed modeling assumptions, these and other results demonstrate that technological advance has the potential to significantly decrease the costs of attaining societal goals for climate change mitigation. However, two market problems must be addressed to maximize the likelihood we will harness these technological opportunities as efficiently as possible. It is important to understand these market problems, and the resulting underinvestment in

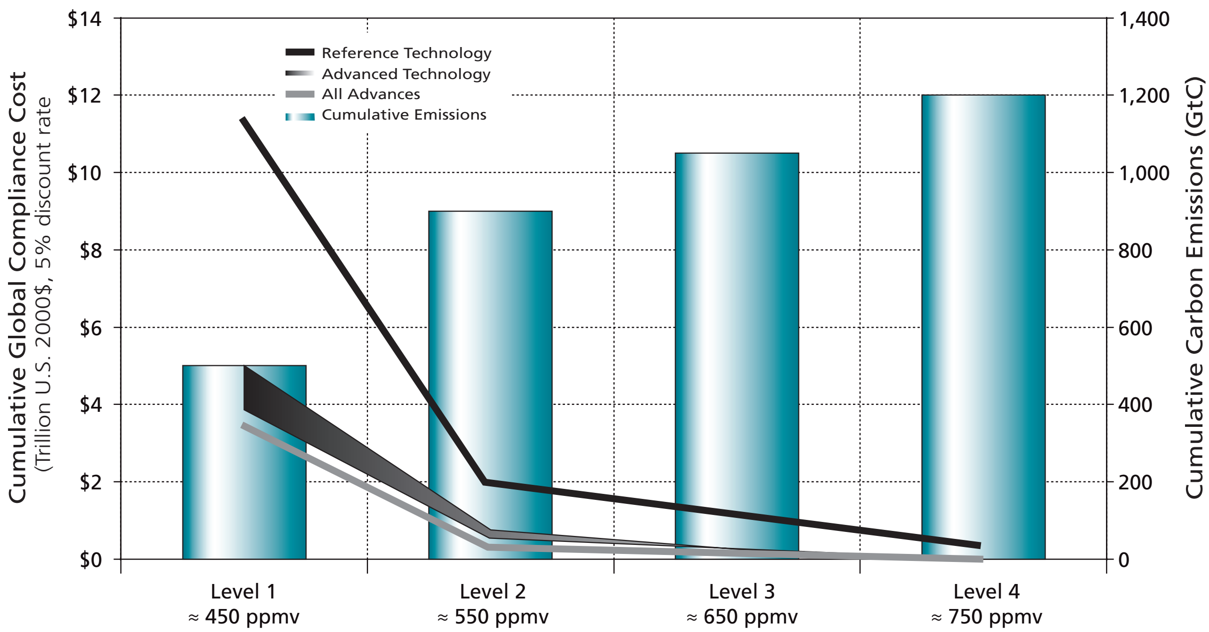
14. For recent surveys of the literature and other overviews of modeling methodology, see Clarke and Weyant (2002); Edenhofer et al. (2006); Edmonds, Roop, and Scott (2000); Gillingham, Newell, and Pizer (2008); Goulder (2004); Loschel (2002); and Weyant (2004). For different views on possible technological options for GHG stabilization see Hoffert et al. (2002); IPCC (2007); and Pacala and Socolow (2004).

15. For example, an analysis by Edmonds et al. (2007, Box 2.3, p. 39) found that in their model the present value cost of achieving stabilization at 550 ppm CO_2 would be more than \$20 trillion greater globally without the reference scenario improvements in technology relative to what was available in 2005. These assumed improvements included advanced energy efficiency, hydrogen energy technologies, advanced bioenergy, and wind and solar technologies.

climate mitigation R&D, in order to structure an appropriate policy response. It is to these market problems that I now turn.

FIGURE 3

Cumulative Global Mitigation Costs under Alternative Technology Scenarios



Source: Clarke et al. 2006, p. 6.5.
Note: Concentrations are ppmv of CO2. Levels do not correspond directly to those in Figure 2.

3. Market Problems, Investment Levels, and the Role of Public Policy

Despite the clear societal benefits of research and innovation for low-GHG technologies, there are two market problems that lead to inefficiently low spending in this area: a lack of private incentive to adopt low-GHG technologies, and underinvestment by industry in R&D, especially basic research. This section describes these two problems, provides evidence on the resulting patterns of R&D spending in the private and public sectors, and finishes by examining the role of public policy given these problems within the context of the innovation system.

3.1. Innovation Market Problems

There are two market problems that lead to inefficiently low investment in climate mitigation R&D and must be addressed in order to face our climate challenge in the most cost-effective way possible (Goulder 2004; Jaffe, Newell, and Stavins 2005; Newell 2007a). First and foremost, there is the environmental externality of global climate change. If firms and households do not have to pay for the climate damage imposed by GHG emissions, then these emissions will be too high. This has implications for technology innovation and adoption because, if there is no demand for GHG reductions, then the demand for GHG-reducing technologies will also be too low. In turn, there will be insufficient incentive for companies to invest in mitigation technology R&D because there will be little market demand for any innovations that might come of it. A market-based emissions policy that places a price on GHGs—through either a cap-and-trade system or an emissions tax—is widely accepted to be a cost-effective response to this problem.[16]

The second market problem relates to the public good nature of technological innovation. The gains from innovative activity are in general difficult for firms to appropriate, as the benefits tend to spill over to other firms and customers, without full compensation. While intellectual property protection (e.g., through the patent system) helps, firms can only capture a fraction, and sometimes a small fraction of the overall gains from innovation. This market problem tends to become greater the farther up in the innovative chain one goes, from development, to applied research, to basic research. The more basic is research the higher is the degree of uncertainty regarding the near-term commercial value of any discovery, as well as one's ultimate ability to capture this value through intellectual property protection or other means. This public good nature of innovation is evidenced in the relatively high social rate of return to innovation relative to private rates that is consistently found by economists (for reviews, see Griliches 1995; Hall 1996; and Nadiri 1993). Typical estimates find the social returns to innovation (as measured, for example, by R&D or patents) are about two to four times as large as the private returns. Others have found similar evidence of high social rates of return in the context of new knowledge for energy innovations and sulfur scrubbing from electric power (Popp 2001, 2003).

While positive knowledge spillovers is a good thing—other things being equal—it leads to private investment in innovative effort that is too low from a broader societal perspective. The problem of private sector underinvestment in research may be exacerbated in the climate context where the incentives for bringing forward new technology rest heavily on domestic and international policies rather than on natural market forces, and where the energy assets involved are often very long lived (so technology turns over slowly). Put another way, the development of climate-friendly technologies has

16. See Kopp and Pizer (2007); Metcalf (2007); and Stavins (2007), for overviews of the issues surrounding the design of domestic U.S. GHG emissions reductions policies, including the advantages and disadvantages of cap-and-trade relative to emissions taxes.

diminished market value absent a sustained, credible government commitment to reducing GHG emissions. Finally, R&D focused on technologies that will lower the costs of dramatic emissions reductions (e.g., zero-emissions energy technologies and associated energy carriers) also serves as a hedge against the possibility that new information reveals climate impacts at the worst end of the spectrum (Baker, Clarke, and Weyant 2006).

3.2. Resulting Patterns of R&D: Follow the Money

These environmental and knowledge externalities have resulted in underinvestment in climate-friendly energy R&D. However, to appreciate the relative capacities of the private, public, and nonprofit sectors to increase such investments, as well as the contrasting capabilities and incentives they face, it is imperative to first understand the basics of the innovation system.

Technological improvement in the economy through the creation and deployment of new product and process innovations is one of the most important underpinnings of economic development as well as broader societal prosperity, including environmental protection. The set of public and private institutions, markets, and governing processes that compose this innovation system is complex, and includes private firms and consortia, their products, their production processes, and the markets within which they operate; government research institutions and public policies; universities and colleges; and other nonprofit research institutions.[17]

One means of describing the innovation system is to follow the money—that is, to summarize the scale of R&D resources being spent, where the funding comes from, and its use.[18] I focus here on R&D broadly within the economy and return to discuss energy R&D more specifically in §4 below. Current estimates are, globally, that nations spend about $1 trillion each year on R&D, with the vast majority of this effort being in the United States and other OECD countries (see Table 2; OECD 2008). Industry is by far the largest player in R&D effort, funding 63 percent and performing 69 percent of R&D globally in 2006 (the most recent year for which complete data are available). Government is the second-largest funder of R&D globally (30 percent), about half of which is transferred to uni-

TABLE 2

International R&D Expenditures in 2006 (units as indicated)

Region	All sources	Percent financed by		Percent performed by			Total researchers
	($ billions)	Industry	Government	Industry	Universities	Government	(million FTEs)
United States	340	66	28	71	14	11	1.4
Total OECD	818	64	30	69	17	11	3.9
Non-OECD*	144	61	32	69	10	20	1.9
World*	962	63	30	69	16	13	5.9

Source: OECD 2008, National Science Board 2008 for U.S. figures.
*Non-OECD total covers only select non-OECD countries and thus the non-OECD and world totals may represent underestimates; however, almost all R&D occurs in the included countries.
Note: Non-U.S. totals are based on purchasing power parity (PPP) exchange rates.

17. See Alic, Mowery, and Rubin (2003) and Norberg-Bohm (2002) for overviews of U.S. technology and innovation policies with lessons for energy and climate change.
18. Innovation activities are of course not limited to R&D, but R&D remains one of the few well-tracked indicators of innovative activity. See National Science Board (2008, p. 4.10) regarding recent developments in metrics for innovation-related activities.

versities, other nonprofit research institutions, and industry who perform the associated R&D within a system of contracts, grants, and other arrangements.

The overall shares of the $340 billion in R&D expenditures in the United States in 2006 are similar to the global averages, with industry funding about two-thirds ($223 billion) and performing 70 percent of all U.S. R&D (Table 2). Overall, U.S. R&D has recently averaged about 2.6 percent of GDP, and industry R&D has averaged 3.7 percent of net sales (National Science Board 2008). The U.S. federal government is the second-largest funder of R&D, providing about 28 percent of total funding in 2006, but most of the associated research is carried out outside the government (Table 3). Besides industry, other key performers of U.S. R&D include universities and colleges (14 percent), the federal government itself (7 percent), government-funded labs or federally funded research and development centers (FFRDCs; 4 percent), and other nonprofit research institutions (4 percent).

In addition to these overall funding levels, it is equally important for policy purposes to understand the composition of R&D—that is, for what type of efforts these resources are spent. To get a handle on the character of this work, the National Science Foundation (NSF) and other agencies divide R&D into three traditional baskets: basic research, applied research, and development (Figure 4). Although these categories have been criticized as being overly simplistic and reinforcing of the idea that innovation is a linear process—rather than one with complex interrelationships and feedbacks—they are nonetheless indicative of a pattern, and in fact the only manner in which data of this type are routinely collected. Moreover, §5.1 argues that an important role for federal funding in GHG mitigation research is in the realm of what could be called strategic or use-inspired basic research, which is research that seeks knowledge and fundamental understanding, but is inspired and guided by practical needs related to GHG mitigation (Figure 5).

TABLE 3

U.S. 2006 R&D, by Funding and Performing Sectors ($ billions unless otherwise noted)

	Source of funds					
Performing sector	All sources	Industry	Federal government	U&C	Other nonprofits	Percent by performer
R&D	340.4	223.4	94.2	12.4	10.5	100
Industry	242.1	219.6	22.6	—	—	71
Industry-administered FFRDCs	2.4	—	2.4	—	—	1
Federal government	24.4	—	24.4	—	—	7
U&C	46.6	2.5	28.5	12.4	3.3	14
U&C–administered FFRDCs	7.7	—	7.7	—	—	2
Other nonprofit institutions	14.3	1.3	5.7	—	7.2	4
Nonprofit-administered FFRDCs	2.8	—	2.8	—	—	1
Percent by funding source	100	66	28	4	3	

Source: National Science Board 2008.
FFRDC = federally funded research and development center; U&C = universities and colleges; — = negligible funds.

FIGURE 4

Stages of R&D: Common Definitions

R&D. According to international guidelines for conducting R&D surveys, R&D comprises creative work "undertaken on a systematic basis to increase the stock of knowledge . . . and the use of this stock of knowledge to devise new applications." (OECD 2002, 30).

Basic research. The objective of basic research is to gain more comprehensive knowledge or understanding of the subject under study without specific applications in mind. Although basic research may not have specific applications as its goal, it can be directed in fields of present or potential interest. This is often the case with basic research performed by industry or mission-driven federal agencies.

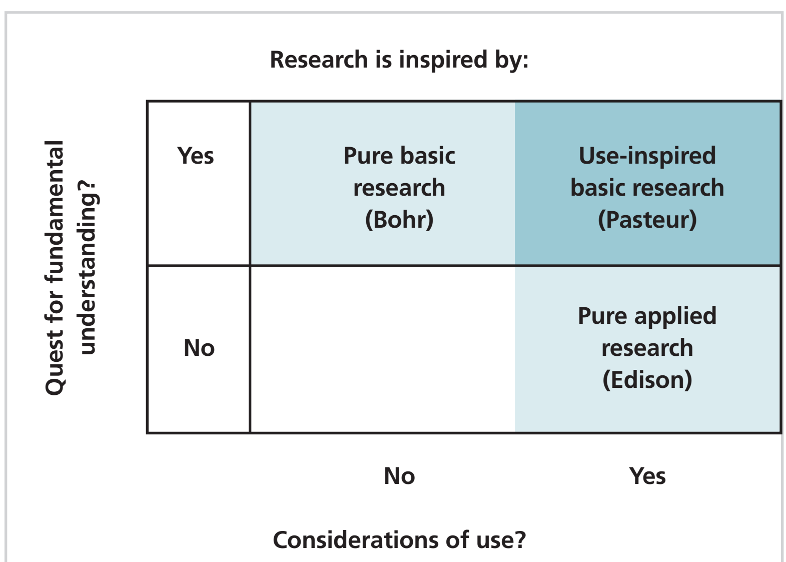
Applied research. The objective of applied research is to gain knowledge or understanding to meet a specific, recognized need. In industry, applied research includes investigations to discover new scientific knowledge that has specific commercial objectives with respect to products, processes, or services.

Development. Development is the systematic use of the knowledge or understanding gained from research directed toward the production of useful materials, devices, systems, or methods, including the design and development of prototypes and processes.

Source: National Science Board 2008, p. 4.9.

FIGURE 5

An Alternative Conception of Research: "Use-inspired" Basic Research



Source: Based on Stokes 1997.

U.S. R&D is dominated by funds for the development of new and improved products, processes, and services by industry, which funded 83 percent and performed 90 percent of all U.S. development in 2006 (Table 4; National Science Board 2008). One sees a similar picture with federal funding for defense-related activities, where 89 percent of R&D funds go for development (National Science Board 2008). In cases like defense where the government is both the funder and the ultimate customer, there is a clear dominance of development activities in the R&D mix.

In contrast, at the other end of the spectrum the federal government is the primary source of U.S. funds for basic research, contributing 59 percent (National Science Board 2008, Table 4). In fact, the vast majority (about 85 percent) of nondefense federal R&D funds go to basic and applied research (OMB 2008 [Table 9.8 in Historical Tables, and

TABLE 4

U.S. 2006 R&D Expenditures by Funder and Stage

(units as indicated)

		Stage		
Funder	Total R&D	Basic research	Applied research	Development
Total ($ billions)	340.4	61.5	74.7	204.3
Percent funded by stage		18	22	60
Industry ($ billions)	223.4	10.6	44.0	168.8
Percent funded by stage		5	20	76
Percent funded of total stage		17	59	83
Government ($ billions)	94.2	36.2	24.9	33.2
Percent funded by stage		38	26	35
Percent funded of total stage		59	33	16
U&C ($ billions)	12.4	8.5	3.1	0.7
Percent funded by stage		69	25	6
Percent funded of total stage		14	4	0
Other nonprofits ($ billions)	10.5	6.3	2.7	1.6
Percent funded by stage		60	25	15
Percent funded of total stage		10	4	1

Source: National Science Board 2008.
U&C = universities and colleges.

Analytical Perspectives]; DOE 2008b). More than half (56 percent) of all basic research is conducted at universities and colleges (National Science Board 2008), with other nonprofits conducting most of the remainder (24 percent).

In addition to creating new knowledge on which further technological development can draw, university-based R&D supports the production of young researchers through strong ties to graduate training and research. Most of these researchers eventually move into the private sector, representing an important link within the overall innovation system. More than half of R&D expenditures (54 percent) are in fact for labor, including wages and fringe benefits (NSF 2007b, Table 7). Therefore, ensuring a stream of scientists, engineers, and other research professionals trained in areas relevant to clean energy technologies will be an important element in increasing the necessary innovative effort and moderating its cost.

3.3. The Appropriate Focus of Public Policies and Investments

Although it may have low short-term returns to individual firms, basic research can have high returns to society over the long run by building the intellectual capital that lays the groundwork for future advances in technology. This economic feature of the innovation system is the principal explanation for the emphasis by industry on development relative to basic research, as well as the rationale for focusing nondefense federal spending on basic and applied research rather than on activities nearer to commercialization. When confronted with limited resources, it is sensible for government policy to focus first and foremost on the part of the innovation problem least likely to be addressed adequately by the private sector.

In addition, by virtue of its critical role in the higher education system, public R&D funding will continue to be important in training researchers and engineers with the skills necessary to work in either the public or private sectors to produce GHG-reducing technology innovations. By supporting graduate and postdoctoral students, public funding for university-based research will expand the economy's capacity to generate scientific advances, technology innovations, and productivity improvements in the future. This linkage has made research funding a priority among many who are concerned about the long-term competitiveness of the U.S. economy and has led to a recent increase in political support for expanded spending—especially on physical sciences and engineering.

Overall, public funding for precommercial research therefore tends to receive widespread support among experts based on the significant positive spillovers typically associated with the generation of new knowledge. Agreement over the appropriate role of public policy in technology development tends to weaken, however, as one moves from support for R&D to support for large-scale demonstration projects, and particularly to deployment. (See Newell [2007b] for a discussion of issues surrounding technology deployment policy.) Economists and other experts generally see clear justification for a government role in supporting research, but much weaker rationales for government intervention in the realms of technology commercialization and widespread deployment.

In situations where there is a missing market for the technology—as is the case for GHG reductions—climate policy that places a price on emissions can serve as the most cost-effective means of encouraging technology deployment. Frustration with the current level of private sector investment in GHG-mitigation technologies should not be taken as an indication the government needs to step in and provide this investment directly, but rather as an indication that the private sector should be given an incentive to do so. Once broad-based GHG emissions policy is in place, many of the existing gaps in green investment currently evident will be filled by the private sector. If specific technology deployment market problems remain even after a GHG emissions price is in place for some time, specific policies can be evaluated to target these problems.

A complete discussion of role and design of technology deployment policies is, however, beyond the scope of this paper.[19]

Technology demonstration projects occupy a middle ground between R&D and deployment. Arguments for public support of technology demonstration projects tend to point to the large expense; high degree of technical, market, and regulatory risk; and inability of private firms to capture the rewards from designing and constructing first-of-a-kind facilities (Newell 2007a). Most compelling from an economic perspective, there may be knowledge generated in the process of undertaking first-of-a-kind demonstration projects—which can help improve the design of future technology, lower technical risks, and serve as a basis for well-designed regulations—but profits from this knowledge may not be appropriable by individual firms. Conversely, caution is required because, despite good intentions, the most notable failures in government energy R&D funding (e.g., the Synthetic Fuels Corporation, Clinch River Breeder Reactor) tend to be associated with large-scale demonstration projects—using up large portions of limited R&D budgets in the process (Cohen and Noll 1991). The recent experience with the FutureGen Initiative for clean-coal power tends to reinforce this perspective.[20] In sum, while it should not be the focus of climate mitigation innovation investments by the public sector, there may be a compelling rationale for well-designed public support for a limited number of first-of-a-kind mitigation technology demonstration projects, so long as the purpose is the generation of substantial new knowledge (as opposed to meeting production or deployment targets).

Finally, growing attention has turned to the possible role of international technology-oriented agreements as part of the architecture of international climate-change policy, including as a key component of the "Bali Roadmap" discussions leading up to the post-2012 successor to the Kyoto Protocol (Newell 2008). Technology-oriented agreements can be aimed at advancing knowledge sharing and coordination, joint R&D, technology transfer, or deployment of technologies—in contrast with agreements framed primarily in terms of emissions targets, such as the Kyoto Protocol (de Coninck et al. 2008). Interest in these efforts is attributable to a number of factors, generally related to the idea that if we can lower the costs of mitigation technologies, the likelihood of significant GHG reductions by countries will be higher. Agreements to further R&D can increase international exchange of scientific and technical information as well as the cost effectiveness of R&D through cost sharing and reduced duplication of effort. Provisions for technology transfer, conversely, are driven primarily by a need to help developing countries follow a less-GHG-intensive development path by providing access to climate-friendly technologies and the funding to cover their additional cost. As such, technology-transfer efforts can help to increase incentives for developing country participation in climate-mitigation agreements and, at the same time, advance goals beyond global climate mitigation (e.g., economic development and local air quality).

19. A number of specific market problems have been suggested as rationales for technology deployment policies. These market problems include information problems related to energy-efficiency investment decisions, knowledge spillovers from learning during deployment, asymmetric information between project developers and lenders, network effects in large integrated systems, and incomplete insurance markets for liability associated with specific technologies (Newell 2007b). Although such problems are often cited in justifying deployment policies, these policies in practice often go much farther in promoting particular technologies than a response to a legitimate market problem would require. Therefore, while conceptually sound rationales may exist for implementing these policies in specific circumstances, economists and others tend to be skeptical that many of them, as actually proposed and implemented, would provide a cost-effective addition to market-based emissions policies. Critics also point out deployment policies intended to last only during the early stages of commercialization and deployment often create vested interests that make the policies difficult to end.

20. Federal government funding for the FutureGen Initiative—a $1.5 billion demonstration plant for producing electricity and hydrogen from coal while capturing GHG emissions—was recently completely reconfigured by the U.S. Department of Energy (DOE) after many years of planning to instead emphasize support of early commercial demonstration of carbon capture at multiple commercial-scale advanced coal-based electric power plants.

4. Inducing Private Sector Innovation through a Market-based Price on GHGs, Reinforced by Permanent R&D Tax Credits

The first part of a cost-effective innovation strategy for climate change mitigation should be to harness the power, efficiency, and flexibility of the private sector. To align private incentives with the public interest, both environmental and knowledge externalities must be addressed. This section thus recommends a comprehensive emissions pricing system reinforced by permanent R&D tax credits, tackling both market problems head on.

4.1. Emissions Pricing Would Encourage Energy Innovation and Cost-Effective Deployment

There are many excellent treatments of the advantages of economywide, long-term, market-based emissions pricing for climate policy; U.S. legislative proposals with the most traction have embraced this approach.[21] Nevertheless, it is worthwhile emphasizing that establishing a GHG emissions price through either a tax or cap-and-trade system is essential *from a technology perspective* for two closely related reasons: First because the GHG price attaches a financial cost to GHGs and—just as people will consume less of something that carries a price than they will of something given away for free—will induce households and firms to buy technologies with lower GHG emissions (a more efficient appliance, for example). Moreover, the GHG price does not encourage just any technology adoption, but rather specifically guides the adoption of the most cost-effective technologies for reducing emissions by sending a consistent financial signal to households and businesses.

The second reason the GHG price is essential from a technology perspective follows from the first because the emissions price creates a demand-driven, profit-based incentive for the private sector to invest effort in developing new, lower-cost climate-friendly innovations. Market-demand pull will encourage manufacturers to invest in R&D and other innovative efforts to bring new lower-GHG technologies to market, just as they do for other products and processes. Economists have investigated this process of induced innovation for many years in the context of a broad set of industries, and more recent evidence supports the inducement mechanism specifically in the context of environmental and energy technology innovation in response to increases in cost of energy and environmental emissions (for surveys, see Jaffe, Newell, and Stavins 2003; and Popp, Newell, and Jaffe 2008). Members of the U.S. Climate Action Partnership [USCAP]—a coalition of major U.S. companies and environmental organizations—agreed when they concluded, "The most efficient and powerful way to stimulate private investment in research, development, and deployment is to adopt policies establishing a market value for GHG emissions over the long term" (USCAP 2007, 5).[22]

For market-based GHG emissions policy to provide an effective inducement to innovation, however, it is critical that the policy be credible to the private sector over the long term. Given the sometimes-substantial time lags between initial discovery and profitable market penetration, companies must be confident there will indeed be sufficient demand once their innovations reach the market. It is therefore critical for policymakers to put in place GHG emissions pricing policies whose stringency is spelled out for many decades in advance, and that provides stable financial incentives across a wide array of technological solutions. An economywide

21. See, for example, Kopp and Pizer (2007); Metcalf (2007); and Stavins (2007), and the other works cited therein.
22. The USCAP companies include Alcan, Alcoa, American International Group (AIG), Boston Scientific, BP America, Caterpillar, Chrysler LLC, ConocoPhillips, Deere, Dow Chemical, Duke Energy, DuPont, Exelon, Ford, FPL Group, General Electric, General Motors, Johnson & Johnson, Marsh, Inc., NRG Energy, PepsiCo, PG&E, PNM Resources, Rio Tinto, Shell, Siemens, and Xerox.

cap-and-trade system or carbon tax, with no expiration date, increasingly stringent targets specified through 2050, and an architecture with sufficient flexibility to adjust over time, should be able to provide this credibility. Under a cap-and-trade system, allowance prices and corresponding financial incentives for technology can also be stabilized through flexibility over time (i.e., through emissions banking and borrowing) and provisions for price floors and price ceilings on emissions allowances (Murray, Newell, and Pizer forthcoming; Newell, Pizer, and Zhang 2005).[23] By setting out a long-term emissions pricing policy designed to provide stable and increasing incentive for GHG mitigation, policymakers will set in motion the most critical element of a robust climate innovation strategy.

4.2. Permanent R&D Tax Credits Would Reinforce Private Innovation Incentives

While private sector incentives for innovation are supported by intellectual property protection, secrecy, and other means, there is still a substantial portion of the benefits of innovation that cannot be captured by innovating firms. This leads to a generic argument in favor of R&D tax incentives to boost the level of private R&D. The U.S. Internal Revenue Code provides for two types of R&D tax incentives—tax credits and expensing.[24] Both apply generally, though not solely, to energy- or climate-related R&D and both give firms incentives to expand research beyond what they would otherwise undertake by reducing the after-tax cost of R&D investments. Section 41 of the tax code allows firms to claim tax credits for extra expenditures on research and experimentation; thus, it is officially known as the R&E, as opposed to R&D, tax credit. In addition, §174 provides for an expensing exception, whereby the taxpayer may treat R&D expenditures as current expenses, rather than charging them to a capital account that would be amortized only over a longer period of time.

The tax credit provided under §41 amounts to 20 percent of qualified research expenditures beyond a firm's baseline level (based on historical research expenditures or an alternative method), with a separate threshold for payments to universities and other nonprofits for basic research.[25] The Energy Policy Act of 2005 also made a change to the R&D tax credit with potential importance for energy and climate technology innovation: corporate payments for energy research to universities, federal laboratories, eligible small businesses, and certain energy research consortia (such as the Electric Power Research Institute) are now eligible for a 20 percent credit, with no threshold (i.e., it applies to all, and not solely incremental, expenditures). Because the credit has no threshold, it is more generous than the other types of R&D tax credits.

The U.S. Treasury estimates the annual cost of the R&D expensing and tax credit incentives at about $5 billion each (OMB 2008 [Analytical Perspectives]); it is unclear how much of this supports energy-related R&D.[26] Overall, econometric studies have found the tax credit is effective in the sense that private sector research spending has increased roughly one-for-one with each dollar of tax credit extended (Hall and Van Reenan 2000). R&D tax

23. Some have criticized price ceilings on allowances, arguing they would weaken or eliminate incentives for private sector innovation and investment in clean technologies. However, this argument is flawed. Curtailing the possibility of very high allowances prices would certainly not eliminate the incentive for clean technology innovation and adoption, although it may curtail the incentive to do so for very expensive technologies that would only be competitive above the ceiling price. Assuming the ceiling price is set appropriately, however, this is desirable because environmental policies should not seek, from an economic perspective, to promote technology at any cost. Rather, policies should induce an *efficient* amount of innovation and adoption, consistent with societal willingness to pay (Kerr and Newell 2003).

24. For general background and recent legislative proposals, see Guenther (2008).

25. Qualified expenses include in-house salaries and supplies, certain time-sharing costs for computer use, and contract research performed by certain nonprofit research organizations. Moreover, these expenses must be incurred in the process of discovering new information the taxpayer could use to develop new products or processes.

26. Permanent extension of the Research and Experimentation tax credit is estimated to cost $51 billion in tax expenditures over the period 2009–13 and $133 billion over the period 2009–18 (OMB 2008b, p. 266).

credits have the advantage of encouraging private efforts to advance technology while leaving to industry the specific R&D decisions and judgments about the most productive areas for investment, given both economic and regulatory incentives. As a result, there is less need for policy intervention in the market and for government to attempt to "pick winners." Tax credits have other advantages over alternative R&D–funding mechanisms: they create less of an administrative burden, obviate the need to target individual firms for assistance, and can be made permanent (and in that case not subject to inconsistent annual appropriations).

Nonetheless, several factors have limited the overall impact of the existing R&D tax credit. First, the credit was originally added to the tax code as a temporary measure; consequently, it has had to be renewed more than ten times, often with modifications. Most recently, the credit expired at the end of 2007 and was not extended until October 2008, when it was retroactively extended until the end of 2009 as part of the Emergency Economic Stabilization Act of 2008. This uncertainty makes long-range research planning based on tax considerations difficult and has led many to call for making the R&D tax credit permanent. Tax credits are also ineffective in situations where a firm has little taxable income, which can be particularly problematic for encouraging R&D by small startup firms. Various reforms to the credit have been proposed to address these and other concerns, such as the definition of qualified research expenses and the thresholds above which the expenses become eligible.[27]

In the context of climate policy, a primary shortcoming of a tax credit approach is the difficulty of targeting R&D efforts that are particularly relevant to GHG mitigation. The recent modification of the existing credit to include contributions for energy research to universities, federal labs, and certain small businesses and research consortia addresses this issue to some extent. In addition, some groups (such as the National Commission on Energy Policy [2004]) have recommended tax credits be increased for technologies aimed at improving end-use efficiency or otherwise reducing GHG emissions. While it would be difficult for Congress and the Treasury to develop workable qualification rules for an augmented R&D tax credit that would focus specifically on efforts relevant for GHG mitigation, the recent provisions specific to energy research suggest it may be feasible in part.

A sensible approach is to make the R&D tax credit permanent.[28] After the special energy-related provisions have been in place for several years (e.g., 2010), the National Academy of Sciences should evaluate the effectiveness of these provisions in boosting energy research and should make recommendations regarding the continued appropriateness of the provisions and potential modification to further increase innovation relevant to GHG mitigation and other energy goals. Nonetheless, despite their value, private sector tax credits for R&D only increase incentives for the type of R&D that firms are naturally inclined to undertake. R&D tax credits must therefore be complemented by increased public funding for the types of innovative effort the private sector is least likely to undertake—namely, innovative effort focused primarily on targeted basic research inspired by mitigation technology needs.

4.3. Impact of Private Sector Innovation Incentives: Who Will Respond?

It is difficult to pin down exactly how much and what type of innovation is likely to be generated by a GHG emissions price and a permanent R&D

27. It has also proved difficult in practice to distinguish expenses that qualify for the credit from other expenses; moreover, under current rules, eligible expenditures are quite restricted. Even if research is considered qualified, related expenses such as overhead and equipment costs are not covered (although certain equipment costs are eligible for accelerated depreciation). See Guenther (2008) for other related issues.

28. Ideally, the tax credit would be, at the same time, subject to appropriate reforms, including those related to issues described above. The details of such reforms are, however, beyond the scope of this paper.

tax credit, but the innovation is sure to come from a wide array of businesses currently engaged in the development and use of energy producing and consuming technologies, especially in the provision of electricity and transportation services. It will also come from the agro-biotech sector (assuming there are incentives for biological sequestration), from companies that produce and consume other non-CO2 GHGs (e.g., chemical companies), and less obvious sectors such as information technologies (e.g., in the context of energy management and conservation).

However, estimates suggest private sector investments in energy R&D have fallen by more than half in real terms from a peak of more than $5 billion per year circa 1980 to about $2 billion per year in 2004, in tandem with declines in energy prices and federal energy R&D spending (National Commission on Energy Policy 2004; NSF 2002, 2007b). Nonetheless, while the trend was clearly downward over this period, private sector R&D investments relevant to energy technology are extremely difficult to assess (see, e.g., President's Council of Advisers on Science and Technology 1997). These estimates provide a poor indication of the overall level of private sector R&D investment that could and likely will be brought to bear on the climate technology challenge. Other studies (Margolis and Kammen 1999; Nemet and Kammen 2007) suggest an alarmingly low (e.g., <0.5 percent) R&D intensity—or ratio of company-funded R&D to net sales—of the energy sector relative to the average R&D intensity of R&D–performing industries, which has been 3.7 percent in recent years (National Science Board 2008). The definition of the energy sector R&D intensity used in such comparisons appears inappropriate, however, and the comparisons themselves across widely different sectors can be misleading (Sagar 2000).

To the contrary, many of the industrial sectors and individual companies that are likely to be most engaged in creating the innovations necessary to reduce GHG emissions have substantial R&D budgets and R&D intensities within the typical range of R&D-performing companies. This is illustrated in Table 5, which shows the 2006 R&D expenditures for a subset of the 1,250 companies that globally had the highest R&D levels (U.K. Department for Innovation, Universities and Skills 2007). The table focuses only on sectors and specific U.S. companies that have the highest relevance to GHG mitigation.

The list in Table 5 includes producers of transportation technologies such as Ford, General Motors, and Boeing, with individual company R&D budgets measured in billions of dollars per year and a global R&D budget for the automotive sector of $80 billion annually. General Electric—which produces a wide array of energy-producing and energy-consuming products, from light bulbs to gas turbines and train engines—has an annual R&D budget of about $3 billion. Chemical and agro-biotech companies, such as DuPont, Dow, and Monsanto, each has R&D budgets near or above $1 billion per year, and will no doubt be active in finding substitutes for GHGs and in engineering low-GHG biofuel alternatives. While elements of the energy sector focused on fossil fuel extraction (e.g., oil and gas companies) have relatively low R&D intensities, they still have substantial R&D budgets in aggregate. Furthermore, elements of the oil services sector that are likely to be important for geologic carbon storage, such as Schlumberger, spend hundreds of millions of dollars annually on R&D and have higher R&D intensities than the large oil companies.

In addition, there are the many smaller firms and start-up companies that have benefited from a recent surge in venture capital investment in clean energy technology. There was about $350 million in early-stage venture capital investment for clean energy in the United States in 2007, approximately double the prior year and starting from a negligible level just ten years ago.[29] While relatively small, such companies can be an important source of produc-

29. Author's analysis based on data from the Thomson Financial VentureXpert database. Other estimates of clean energy venture capital investment, which tend to be much higher, include large amounts of funding for expansion and later-stage financing.

TABLE 5

R&D of Select Sectors and U.S. Companies Active in Climate-relevant Technology, 2006
(units as indicated)

Company	R&D ($ millions)	(percent of sales)
All sectors (1,250 top companies globally)	478,129	3.5
Aerospace & defense (39 top companies globally)	21,160	4.9
Boeing	3,262	5.3
United Technologies	1,531	3.2
Automotive (78 top companies globally)	80,284	4.1
Ford	7,210	4.5
General Motors	6,609	3.2
Delphi	2,103	8.0
Visteon	595	5.2
Johnson Controls	421	1.3
Chemicals (91 top companies globally)	22,341	3.1
DuPont	1,304	4.7
Dow	1,166	2.4
Monsanto	726	9.9
Construction and materials (23 top companies globally)	2,374	0.9
Owens Corning	60	0.9
Lennox	42	1.1
Electricity (16 top companies globally)	2,918	0.9
Electronic and electrical equipment (102 top companies globally)	35,150	4.5
Agilent Technologies	656	12.8
Danaher	447	4.6
General industrials (36 top companies globally)	11,583	2.1
General Electric	2,973	1.8
Honeywell	1,413	4.5
Household goods (24 top companies globally)	5,011	2.3
Whirlpool	429	2.3
Industrial engineering (70 top companies globally)	11,737	2.7
Caterpillar	1,349	3.2
Deere	727	3.7
Industrial metals (23 top companies globally)	3,201	0.8
Alcoa	213	0.7
Oil and gas (18 companies globally)	6,465	0.3
ExxonMobil	734	0.2
Chevron	469	0.2
Oil equipment services and distribution (10 companies globally)	1,748	1.9
Schlumberger	620	3.2

Source: Selected from the *R&D Scorecard's* 1,250 companies globally with the highest R&D expenditures (U.K. Department for Innovation, Universities and Skills 2007).
Note: Specific U.S. companies listed had R&D expenditures above $400 million in 2006, with the exception of Owens Corning, Lennox, and Alcoa, which also were included. R&D includes amounts funded by only the companies themselves, not by the government or others under contract. Based on OECD international R&D data (Table 2), these 1,250 companies account for about 80 percent of global industry R&D.

tive innovative effort (Kortum and Lerner 2000).

The overall level of energy investment expected over the next few decades provides another indication of the scale of relevant private sector investment. The IEA in its most recent assessment of energy investment projects that about $22 trillion of investment in energy-supply infrastructure will be needed over the 2006–30 period, or almost $900 billion annually on average (IEA 2007b). Note this does not include investment in energy demand-side technologies (e.g., transportation, appliances, and equipment) which measure in the trillions of dollars each year. Assuming the level of associated private R&D investment is measured in terms of a few percent of sales, as is typical, this implies private sector innovative efforts on energy-related technologies measured in tens of billions of dollars per year. This is consistent with a recent IEA (2008) estimate placing current global private sector spending on energy technologies at $40 billion–$60 billion annually, far exceeding public sector energy spending of about $10 billion annually.

Three main messages emerge from the discussion thus far. First, there is substantial R&D capacity in the principal sectors and companies that purchasers of energy technologies will turn to for lower-GHG alternatives. Past evidence both broadly in the economy and specifically in the energy sector indicates this private sector innovative capacity will be directed to developing and commercializing low-GHG technologies—if there is a financial incentive provided by increased demand due to a price on GHGs. The second message is that the private sector level of R&D spending on relevant products and processes is likely to be so substantial that, if private sector profit incentives are not clearly aligned with societal GHG reduction goals, then any public R&D spending will likely be pushing against an insurmountable tide. Finally, the recognition that the private sector has substantial resources for innovation, as well as the incentive to focus on very applied research and especially development and deployment, suggests public funding should complement these efforts by prioritizing targeted basic research rather than substituting for or duplicating private innovative activities.

5. Complementing Private Innovation through Effective Expansion of Federal Resources for Climate Mitigation R&D

While it is imperative to harness the private sector capacity for climate mitigation R&D, this alone would be an insufficient climate change innovation strategy. This section examines the rationale for further government support of strategic basic research inspired by climate technology needs and proposes a plan to efficiently increase spending. To ensure existing and additional resources are efficiently employed, it also emphasizes the need for an effective management and coordination strategy. Finally, it proposes increased use of innovation inducement prizes for targeted technological breakthroughs.

5.1. Background: Increased Federal Funding for GHG Mitigation Research Would Usefully Complement Private Innovation Efforts

While private sector effort dominates overall R&D spending and performance—particularly for product and process development—government funding of research is a significant and essential component of the overall innovation system, including the role it plays in training future researchers. Universities, other nonprofits, and federal labs perform more than 85 percent of U.S. basic research, more than half (59 percent) of which is funded by the federal government (National Science Board 2008). Legislative and executive branch policymakers must therefore make decisions on how much to spend on federal R&D, where to spend it, and how to manage this research portfolio.

The U.S. federal R&D budget was $135 billion in 2007, 60 percent of which went for defense and 40 percent for nondefense R&D (Table 6).[30] More than half (54 percent) of federal nondefense R&D spending went for health-related research through the National Institutes of Health, with space research and technology (NASA) and general science (NSF) commanding the second- and third-largest components at 15 percent ($8.3 billion) and 7 percent ($4.0 billion) of nondefense R&D, respectively. Whereas the R&D budget managed by the U.S. Department of Energy (DOE) totaled almost $8 billion, only about half of this total was for energy-related research ($3.9 billion), with the remainder going to nonenergy basic research (e.g., biological, environmental, nuclear physics, and defense-related research).

Thus, publicly funded energy research constitutes about 7 percent of the nondefense and 3 percent of the total federal R&D budget (or less than 0.03 percent of GDP). This includes applied research within the DOE program offices (Energy Efficiency and Renewable Energy, Fossil Energy, Nuclear Energy, and Electricity Delivery and Energy Reliability), as well as basic science research conducted through the DOE Office of Science programs on Fusion Energy Sciences and Basic Energy Sciences (e.g., materials science and engineering, chemistry, geosciences, and biological energy sciences). See Table 7.

To place this in some perspective, health expenditures accounted for 16 percent of U.S. GDP in 2006 (U.S. Department of Health and Human Services 2008), energy expenditures accounted for 8 percent of U.S. GDP in 2005 (EIA 2008a), and agriculture accounted for about 1 percent of U.S. GDP in 2004 (World Bank 2007). The most significant trend in recent years in federal R&D spending has been the large rise in health-related R&D, which has increased from 25 percent ($8 billion in real 2007 dollars) of the federal nondefense R&D budget in 1980 to 54 percent ($29 billion) in 2007 (OMB

30. Note that there is a significant discrepancy between federal R&D funding levels reported in R&D surveys (Table 3 and Table 4) and in the federal budget (Table 6). See National Science Board (2008) for discussion of this discrepancy.

TABLE 6

U.S. Federal Budget for R&D by Agency and Stage (FY2007)

($ billions unless otherwise noted)

Agency	Percent of total R&D	Total R&D	Basic research	Applied research	Development
Dept. of Health and Human Services	21	29.0	15.6	13.4	—
National Aeronautics and Space Administration	6	8.3	1.8	0.9	5.6
National Science Foundation	3	4.0	3.6	0.4	—
Dept. of Energy (energy-related)	3	3.9	1.5	1.2	1.2
Dept. of Energy (other non-defense)	1	1.6	1.6	—	—
Dept. of Agriculture	2	2.2	0.9	1.1	0.2
Other agencies	4	4.8	0.8	3.2	0.8
Non-defense total	40	53.6	25.8	20.1	7.7
Percent of non-defense R&D by stage		100	48	38	14
Dept. of Defense	58	78.3	1.5	5.1	71.6
Dept. of Homeland Security	1	1.1	0.2	0.4	0.4
Dept. of Energy (defense-related)	2	2.3	—	1.5	0.8
Defense total	60	81.7	1.8	7.0	72.9
Percent of defense R&D by stage		100	2	9	89
Total federal R&D	100	135.3	27.6	27.1	80.6
Percent of total R&D by stage		100	20	20	60

Source: OMB 2008a, 2008b; DOE 2008b.
— = negligible funds.
Note: Applied research and development spending for DOE energy-related research is apportioned equally based on data for FY2006.

TABLE 7

Energy R&D Budget for U.S. Department of Energy

($ millions)

Office	FY 2006 actual	FY 2007 actual	FY 2008 estimate	FY 2009 request
Energy efficiency and renewable energy	827	1,156	1,420	1,175
Electricity transmission and distribution	133	97	110	100
Nuclear energy	431	493	962	854
Fossil energy	581	581	743	754
Basic energy sciences	1,110	1,221	1,270	1,568
Fusion energy sciences	281	312	287	493
Total	3,362	3,859	4,790	4,944

Source: DOE 2007, 2008b.
Note: Energy Efficiency and Renewable Energy budget excludes funding for weatherization, intergovernmental activities, and the federal energy management program.

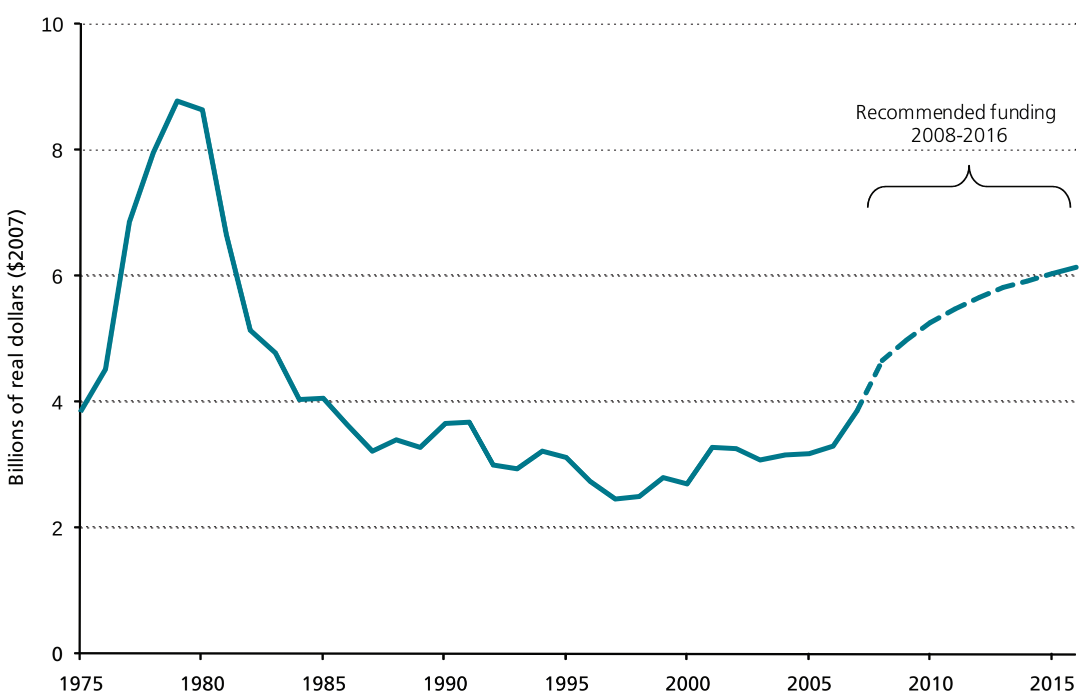
2008 [Historical Tables, Table 9.8]). Over the same period, energy R&D funding halved from a high of more than $8 billion (in real 2007 dollars) to about $4 billion currently, or from 25 percent to 7 percent of nondefense federal R&D spending, where it has roughly been for the past decade (Figure 6). Low fossil fuel prices, deregulation of the natural gas and electric utilities industries, and other factors led to substantial reductions in private sector R&D expenditures, while efforts to balance the federal budget, some notable energy R&D failures, and a lack of political interest led to a tandem decline in federal energy R&D spending. While much of this decrease may have been warranted at the time, the new energy technology challenges posed by global climate change and concerns over energy security have significantly increased the prospective value of increased public funding for energy-related research. In response, the trend appears to be changing, with the most recent budget requests and congressional appropriations increasing energy R&D measurably.

But how high should the federal energy R&D budget go? And how fast should it rise? Ideally one would like to optimally determine and allocate the federal R&D budget across the wide variety of funded areas—thorough detailed evaluation of the technical opportunities, cost of research efforts, likelihood of success, related private sector R&D, and ultimate economic and social payoff of research. While this is not practical at present, we are not entirely in the dark, and a number of facts suggest that a significant expansion of well-directed energy R&D funding is warranted.

Foremost, there is the magnitude of the cost of proposed climate mitigation policies. Recall that in §2.3 we found the cost to the United States of GHG mitigation through 2050 could be on the order of $1 to $10 trillion (<1 to 3 percent) of discounted GDP, or an annualized $50–$500 billion per year. In §2.4 we also found that advanced technology holds the potential to lower these costs by tens to hundreds of billions of dollars annually in

FIGURE 6

U.S. Federal Energy R&D Spending (1975–2007) with Recommended Projections



Source: IEA 2007a, DOE 2008b, and author's calculations.
Note: The projections assume a 3 percent inflation rate so that $8 billion in nominal terms in 2016 is equivalent to $6.1 billion in real terms.

the United States and hundreds of billions to trillions of dollars on a cumulative basis. Global cost savings from technological advance could be several times this level, and potentially increase the prospects for broader and deeper participation of other countries in GHG mitigation. For example, recent IEA (2008) and UNFCCC (2007) assessments of financial requirements to respond to climate mitigation needs, estimate the necessity of at least doubling clean energy R&D globally to stabilize or significantly reduce GHG emissions within the next several decades.

Studies that have also considered the energy security (e.g., oil and broader energy market disruptions) and conventional air pollution benefits of energy R&D find that these concerns further significantly increase the value of energy R&D (Schock et al. 1999). Importantly, many innovations that address climate concerns also address concerns associated with energy security and local pollution, as well as yielding broader economic benefits. It will therefore be valuable to target funding at areas having the prospect to address multiple energy challenges at the same time. Innovations that increase energy efficiency clearly hold this potential, as do supply-side innovations for renewable energy, advanced nuclear power, and CCS that increase fuel diversity at the same time they reduce multiple pollutants.

5.2. Proposal to Double Federal Climate Mitigation R&D Spending Over the Next Eight Years

A plan to roughly double federal climate mitigation R&D spending over 2007 levels, to $8 billion by 2016, is sensible, with periodic external, independent evaluation during this period and further expansion of effort beyond this point if justified.[31] Figure 6 shows the last three decades of federal energy R&D spending in real terms, along with recommended funding increases over the next four to eight years. (Note the projections assume a 3 percent rate of inflation, so that $8 billion in nominal terms is equivalent to $6.1 billion in real terms.) These gradual increases would represent cumulative additional spending of about $22 billion through 2016 over 2007 levels of about $4 billion. This magnitude of recommended climate mitigation R&D spending is easily consistent with reasonable assumptions about expected GHG mitigation costs, the prospects for R&D to lower those costs, and thus the rate of return to such R&D.[32]

Ramping up research efforts at a significantly more rapid pace runs the risk of outstripping the capacity of R&D managers and researchers to effectively allocate and absorb the additional resources, thereby leading to waste.[33] Increased demand for specialized R&D effort without a complementary increase in the supply of relevant R&D professionals also runs the risk of displacing or crowding out other valuable research activities, or of increasing salaries rather than effort. In addition, once R&D levels approach a desired longer-term level, the rate of growth should be gradually slowed rather than abruptly stopped in order to avoid a situation where the level of research support is insufficient to accommodate newly graduated researchers entering the workforce. One way to avoid this risk is to increase innovative efforts gradually, and at the same time to emphasize graduate student and early

31. Other suggestions that what we really need is a Manhattan Project or Apollo Project approach to climate mitigation R&D are misguided, however, for several reasons. For both of those efforts the government was the sole customer for a single, well-defined project, versus the millions of diverse users of a multitude of technologies that characterize energy technology markets. Cost was also not a key concern with those earlier projects, whereas with climate technology innovation cost competitiveness is the central issue. Those efforts also gave rise to a relatively short-lived burst of spending to solve a discrete problem, whereas what is likely to be required for climate technology innovation is steady incremental improvement over many decades. See Yang and Oppenheimer (2007) for a related discussion.

32. For example, assuming GHG-mitigation costs of $100 billion annually, and assuming these costs could be lowered by 10 percent through publicly funded energy R&D, $8 billion annually of R&D spending is consistent with a 25 percent rate of return to R&D ($100B x 10% = $8B x 1.25).

33. For example, Freeman and Van Reenan (2008) found that the rapid increase in spending by the National Institutes of Health during 1998–2003 (which almost doubled in real terms over five years), and then the ensuing deceleration, created substantial adjustment problems in the market for research.

career researcher support within public R&D funding (Freeman and Van Reenan 2008).

This increased funding should prioritize strategic basic research inspired by critical needs arising from efforts to develop new and improved GHG-mitigation technologies, and at the same time invests in training the next generation of scientists and engineers. This would tend to imply prioritizing additional funding to universities, which receive only about 15 percent of current DOE energy R&D funding, while government laboratories receive about two-thirds. In order to encourage exploration of novel, emergent, or integrative concepts for addressing climate change, funding should also be increased for exploratory research that pursues transformational technologies that may not fit well within existing basic or applied research programs.[34] In unusual cases where there is a compelling need for public funding and collaboration for first-of-a-kind technology demonstration, such projects should be carried out in close partnership with industry and should be focused on knowledge generation, as opposed to meeting production targets or deployment goals.

Some would argue with this focus. On one end of the spectrum, some take the perspective that the government should only fund the most basic type of scientific research, with limited regard to ultimate application. They would argue that to do otherwise is to meddle in the private sector. Others contend that the focus should be on near-term commercialization and deployment, in order to help get clean energy technologies into the marketplace as soon as possible. From this perspective, R&D does not generate near-term GHG reductions.

Neither of these perspectives seems justified. While funding basic science relevant to energy production and use is clearly an essential role for the federal government—a role that should be continued—a more strategic focus is also necessary to ensure knowledge is created that is directly relevant to lowering the costs and expanding opportunities for GHG mitigation. At the other extreme, a focus on near-term deployment and large-scale demonstration spends scarce resources on efforts that are more effectively and efficiently undertaken by the private sector, induced by a GHG emissions price. In addition, under a cap-and-trade system, technology deployment programs do not generate any additional emissions reduction, which are determined by the cap. Instead, these policies simply reorient the technologies used to limit emissions to the cap, and in doing so tend to increase overall costs.

The concept of strategic basic research emphasized here is close in spirit to Stokes's (1997) notion of use-inspired basic research, which unlike pure basic research, is inspired by the desire to develop improved technology, but unlike pure applied research, also seeks to develop improved fundamental understanding. This orientation is particularly evident in a series of workshops and reports on basic research needs, sponsored by the DOE Basic Energy Sciences Program, and culminating in a recent announcement of awards for several Energy Frontier Research Centers.[35]

In 2001, the Basic Energy Sciences Advisory Committee (BESAC 2003) started a process to assess the scope of fundamental scientific research necessary to address DOE missions in energy efficiency, renewable energy sources, improved use of fossil fuels, nuclear energy, future energy sources, and re-

34. An exploratory research program could support high-risk, long-term, out-of-the-box concepts, in contrast to a more traditional focus emphasizing advances applicable to more familiar technologies (DOE 2006). The success of an exploratory research program, as well as the encouragement of greater risk taking within basic research programs, will depend in part on a greater willingness to tolerate individual project failures. In addition, the process for soliciting ideas and awarding grants for such research would need to explicitly encourage imaginative and fresh thinking, and award criteria may need to deemphasize a traditional focus on prior research and strong evidence of likely success.

35. Also see recent strategic planning efforts under the U.S. Climate Change Technology Program (Brown et al. 2006; DOE 2006).

duced environmental impacts of energy production and use (BESAC 2003; DOE 2008a).[36] That study inspired a series of ten follow-on reports on basic research needs, based on workshops with university, national lab, government, and industry scientists over the past six years on

- the hydrogen economy,
- solar energy utilization,
- superconductivity,
- solid-state lighting,
- advanced nuclear energy systems,
- clean, efficient combustion of transportation fuels,
- electrical-energy storage,
- geosciences and the long-term storage of nuclear waste and CO_2,
- materials under extreme environments,
- catalysis for energy-related processes,
- as well as a report on grand challenges in directing matter and energy (BESAC 2007).

To implement the collective recommendations from this process, the DOE Office of Basic Energy Sciences is pursuing two complementary approaches: multi-investigator research via several new Energy Frontier Research Centers and a significant increase in single-investigator and small-group projects that currently form the bulk of its core research portfolio. The current plan is for the Energy Frontier Research Centers awards to be in the $2 million–$5 million range annually for an initial five-year period and for approximately $100 million to be available for multiple center awards starting in FY2009. Examples given by DOE of possible research topics include the following (DOE 2008a):

- Direct conversion of solar energy to electricity and chemical fuels
- Understanding of how biological feedstocks are converted into portable fuels
- New generation of radiation-tolerant materials and chemical separation processes for fission applications
- Addressing fundamental knowledge gaps in energy storage
- Transforming energy utilization and transmission
- Science-based geological carbon sequestration

For example, without effective electrical energy storage, intermittent renewable energy sources (e.g., wind and solar) cannot significantly displace fossil and other conventional sources of electricity (DOE 2008a). Likewise, current battery technologies are limited, impeding performance and making plug-in hybrid or all-electric cars prohibitively costly. Fundamental research in electrical energy storage can accelerate scientific discoveries to help bridge these gaps in cost and performance relative to existing technologies. This is just one example of how targeted, strategic basic research motivated by GHG reduction and other energy goals has the potential to make a significant contribution to an overall climate policy strategy. Many other studies have identified a wide range of specific research needs for advancing energy technologies critical to GHG mitigation (see, e.g., Brown et al. 2006; DOE 2006; Massachusetts Institute of Technology [MIT] 2003, 2007; National Research Council [NRC] 2004).

Coming from many different perspectives—including concerns over climate change, energy security, and economic competitiveness—a number of other studies have also recommended significant increases in federal energy R&D spending, both with respect to basic research (particularly in physical sciences and engineering; see National Academy of Sciences 2007), as well as on the more applied end of the research spectrum (National Commission on Energy Policy 2004; Ogden, Podesta, and Deutch 2007;

36. BESAC was established in 1986 to provide independent advice to the DOE Basic Energy Sciences program on research and facilities priorities; proper program balance among disciplines; and opportunities for interlaboratory collaboration, program integration, and industrial participation. BESAC includes primarily representatives from universities, national laboratories, and industries involved in energy-related scientific research. See http://www.sc.doe.gov/bes/BESAC/BESAC.htm.

President's Council on Science and Technology 1997). Such recommendations have already made their way into specific legislation, including the Energy Policy Act of 2005 and the America Competes Act (passed August 2007).

Among other things, the Energy Policy Act of 2005 authorizes increases in the DOE budgets over 2007–09 for the applied research programs (energy efficiency, renewable energy, distribution, fossil energy, and nuclear energy), as well as basic energy sciences, that are easily on track to double those research budgets by 2016. The American Competes Act also authorizes increases in the budgets of the DOE Office of Science and other research agencies (the National Institute of Standards and Technology and NSF) through 2010 that would, if maintained, double these research budgets over about seven years (Stine 2008a). The primary legislative hurdle remaining appears to be with respect to appropriations, avoidance of excessive earmarking of those appropriations, and maintaining commitment. At an authorization level, the notion of significantly increasing these research budgets already commands substantial support.

Thus, a major concern for federal energy R&D is funding. Decisions about the funding source or sources to be used for these programs have consequences for the magnitude and continuity of financial support in the future, as well as implications for the institutional management of funds and the degree and nature of government oversight. Increased funding could come from general revenue sources; from revenues generated by emissions taxes or the sale of emissions allowances; or from wires and pipes charges on electricity and other fuels. In a federal fiscal context requiring budget neutrality, it may also be necessary to couple proposals for increased R&D spending with revenue-raising proposals. In that context, it may make pragmatic sense to couple emissions pricing or other provisions that raise revenue, with proposals for increased federal R&D funding and permanent R&D tax credits—regardless of whether there is explicit earmarking in the legislation. See Newell (2007a) for further discussion of these options.

Recent cap-and-trade proposals in the U.S. Congress have in fact targeted a significant portion of the value of emissions allowances (through either auctions or direct allowance allocations) to support low-GHG technologies. For example, estimates released along with the Boxer substitute to the Lieberman-Warner Climate Security Act (S. 3036) identify allowance-based allocations valued at more than $700 billion through 2050 (out of total allowance allocations valued at an estimated $6.7 trillion) for a variety of energy technology programs, including for energy efficient transportation and buildings, renewable energy, low-carbon electricity generation, carbon capture and sequestration, and international technology transfer.

However, as currently written virtually all of the more than $700 billion in allocations is targeted at commercial technology *deployment* as opposed to research efforts of the type emphasized in this paper. For instance, the only provision in S. 3036 targeted toward R&D is an allowance allocation valued at $17 billion through 2050 (or about $500 million annually on average) for the Energy Transformation Acceleration Fund. This fund has been established in the Treasury for the Advanced Research Projects Agency-Energy (ARPA-E), a new agency authorized within the Department of Energy by the America Competes Act of 2007, although ARPA-E has not yet been funded through appropriations.[37] As discussed elsewhere in this paper, such a focus is too limiting given the existing institutional structures in DOE that manage energy research (e.g., DOE Office of Science and other DOE program offices).

37. Now that it has been established (at least on paper), the question remains what an ARPA-E—with its own director, advisory board, and budget—could accomplish in practice that is distinct from the broader DOE mission and institution. For further discussion of the history, goals, and evaluation of the ARPA-E concept, see Newell (2007a) and Stine (2008b).

A further issue with the current structure of these provisions is that they allocate a fixed percentage of allowance revenues to specific purposes, the dollar value of which will depend on the number of auctioned allowances, the level of the allowance price, and in turn on uncertain economic conditions. A more appropriate approach would be to allocate a dollar amount, as in usual appropriations, or at a minimum to subject any percentage based allocations to dollar caps. There is no reason to think that the appropriate level of expenditure on these programs is directly proportional to the value of emissions allowances.

5.3. Effective Management and Coordination Would Ensure that Existing and Additional Resources Are Employed Efficiently

At present, the federal government sponsors R&D on GHG-reducing technologies primarily through grants and contracts awarded to national labs, universities, and industry for energy-related research. This research support is administered largely by the DOE Office of Science and the DOE program offices: Energy Efficiency and Renewable Energy, Fossil Energy, and Nuclear Energy. (See DOE organizational chart in Figure 7.) The NSF and other federal agencies also fund research relevant to energy and climate-mitigation technology, but these efforts tend to be on a smaller scale and, particularly in the case of NSF, are focused more on general science.[38] Federal grants and contracts fund both research centers and individual projects, and are often but not always awarded through a competitive process involving a request for proposals, proposal review, and selection.

The current interagency oversight structure for this research is the Climate Change Technology Program, a counterpart to the Climate Change Science Program, which focuses on the natural science of global warming and climate change processes (Figure 8).[39] Analogous duel structures also existed during the Clinton administration, and effective interagency structures for coordinating both climate change science and climate change technology initiatives among the Office of the President and relevant departments will be essential in the next administration.

Within DOE, the Office of Science focuses on basic research, while the program offices focus almost entirely on applied R&D. The DOE Office of Science is the largest single supporter of U.S. basic research in the physical sciences, accounting for 40 percent of federal outlays in this area. Of the thirty-seven currently active FFRDCs, DOE sponsors sixteen—more than any other agency.[40] Otherwise known as the national labs, these sixteen FFRDCs perform about two-thirds of DOE-funded energy R&D and receive about 95 percent of their funding from the federal government. FFRDCs administered by universities and other nonprofit entities receive the majority of funding, with the remainder going to industry-run FFRDCs, industry, universities, and other nonprofit research organizations. Table 8 shows how this funding was distributed to different entities engaged in energy R&D in FY2006.

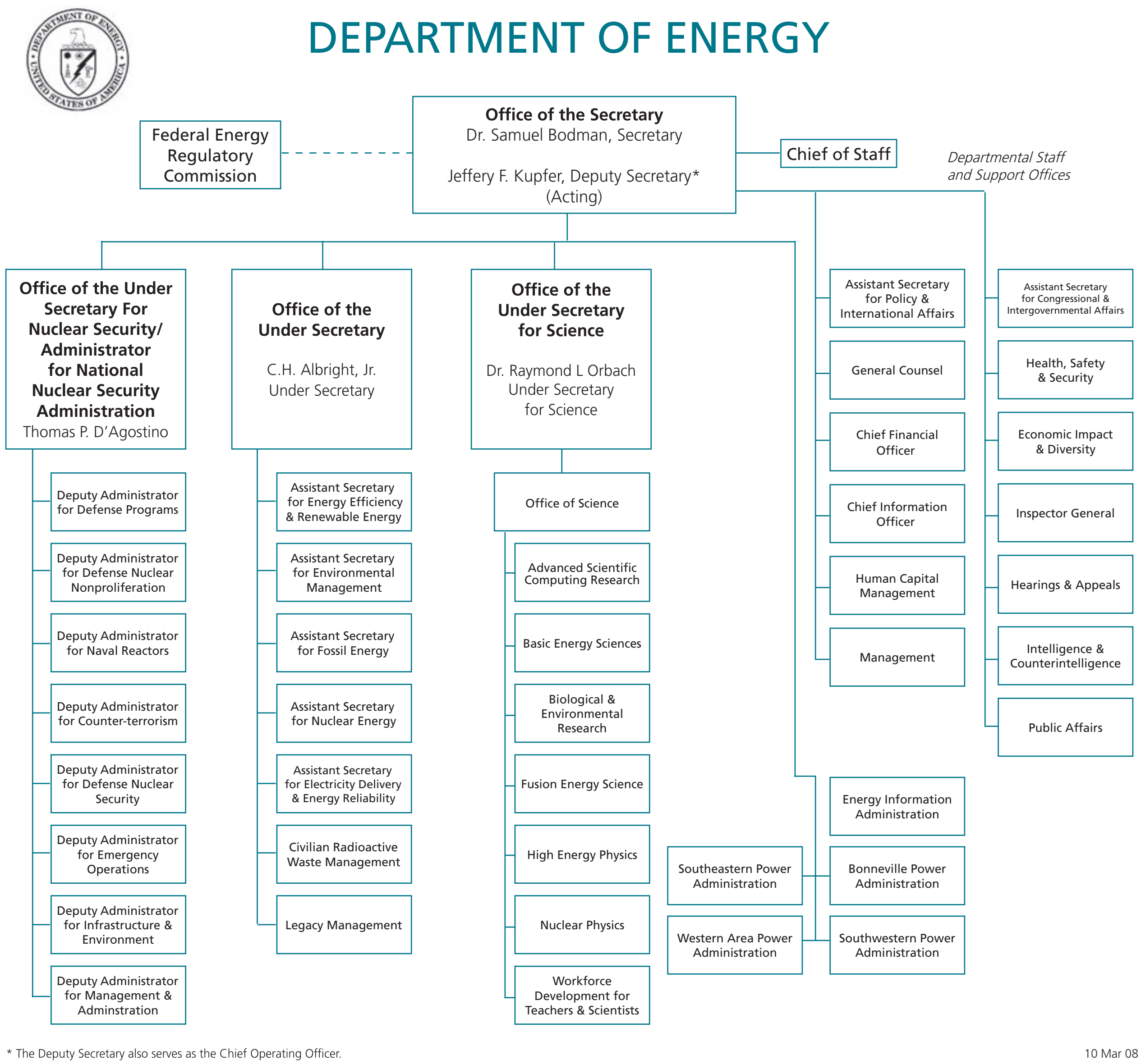
DOE energy research has gone through several transitions over the past three decades, both in terms of its relative focus on precommercial basic research versus technology demonstration, and in terms of the emphasis placed on different technology areas

38. OMB (2007) identified about $370 million in climate change technology-related outlays in 2007 at agencies other than DOE (i.e., NASA, EPA, DOD, USDA, NSF, DOT, DOC [NIST]), or less than 10 percent of overall federal climate technology R&D spending.

39. The Energy Policy Act of 2005 explicitly authorized the Climate Change Technology Program, administered within DOE's Office of Climate Change Policy and Technology.

40. See http://www.nsf.gov/statistics/nsf06316/ for a master list of all FFRDCs. The main DOE labs focused on energy science and technology are the university-administered Ames, Argonne, Lawrence Berkeley, and Fermi labs; the industry-administered Idaho lab; the nonprofit-administered National Renewable Energy, Oak Ridge, and Pacific Northwest National labs; and the DOE-administered National Energy Technology Laboratory. All are overseen by the DOE Office of Science, except for the National Renewable Energy Laboratory, the National Energy Technology Laboratory, and the Idaho National Laboratory, which are overseen by DOE's Energy Efficiency and Renewable Energy, Fossil Energy, and Nuclear Energy program offices, respectively.

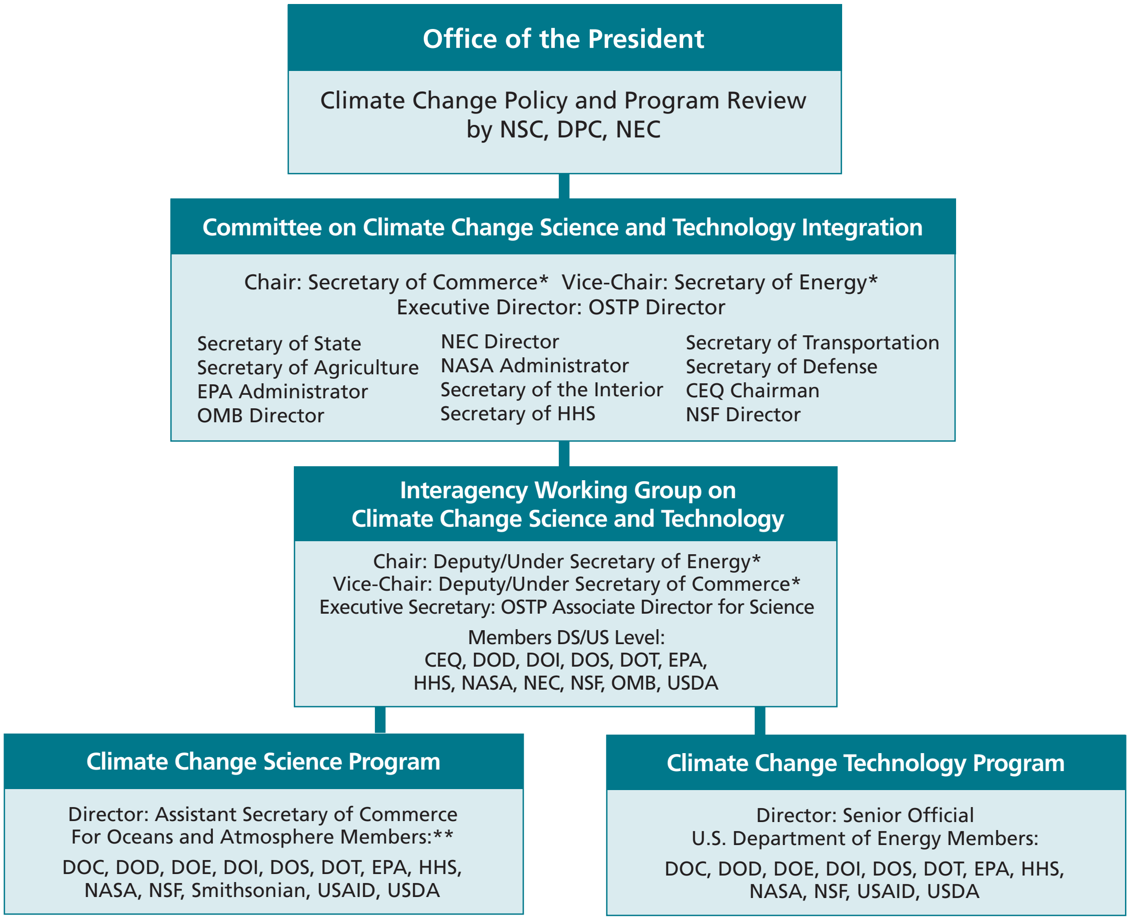
FIGURE 7
U.S. Department of Energy Organizational "Stovepipes"



Source: www.energy.gov/organization/orgchart.htm.

FIGURE 8

Current Cabinet-Level Committee on Climate Change Science and Technology Integration



*Chair and Vice Chair of Committee and Working Group alternate annually.

**CEQ, OSTP, and OMB also Participate

Source: DOE 2006, p. 4.

TABLE 8

U.S. Department of Energy R&D Budget by Performer (FY2006) (percent)

Office	Total	Intramural	FFRDCs			Industry	Universities	Nonprofit
			Industry	University	Nonprofit			
Energy Efficiency and Renewable Energy	100	37	7	9	35		10	3
Basic research	3	1	1		1			
Applied research	41	16	4	4	12		4	1
Development	50	20	2	5	18		5	1
R&D plant	5				5			
Fossil Energy	100	23	1	4	5	52	10	5
Basic research	2						2	
Applied research	43	6	1	1	1	24	8	1
Development	55	17		3	4	28		4
Nuclear Energy	100		24	16	36	7	13	
Applied research	99		24	16	35	7	13	
Development	1				1			
Office of Science	100	2	2	49	25	4	17	1
Basic research	84	2	2	39	20	4	17	1
R&D plant	16			10	5			
Total	100	9	4	37	25	9	15	2

Source: NSF 2007a.
Note: Based on $4.5 billion in R&D spending by the DOE program offices and Office of Science (which also supports non-energy related research).

(e.g., nuclear power, fossil fuels, energy efficiency, and renewables). (See NRC 2001 for a brief history.) Along the way, the department's research objectives have also shifted from addressing concerns related primarily to energy security and resource depletion to a greater emphasis on environmental issues.

While the energy independence goal of the Nixon administration's Project Independence quickly proved impractical, government policy with respect to energy R&D stressed the development of alternative liquid fuels well into the 1980s. This emphasis culminated in the creation of the Synthetic Fuels Corporation in 1980, which became emblematic of the large, expensive demonstration projects undertaken during that era (Cohen and Noll 1991). The following year, the incoming Reagan administration dramatically changed the direction of national energy policy; federal research goals began to stress long-term, precompetitive R&D and lower overall budgets. The 1980s were mostly a time of retrenchment for DOE's research program, although funding levels stabilized in the late 1980s and early 1990s. Congressional appropriations also began to emphasize environmental goals at that time, with large expenditures for the Clean Coal Technology demonstration program.

The shift to a greater emphasis on environmental goals, energy efficiency, and renewable energy, public-private partnerships, competitive award processes, and cost sharing with industry continued over the course of the Clinton administration in the 1990s. A number of studies over the past several years have evaluated the performance of federal energy R&D programs.[41] Although these R&D programs have produced some notable failures and although their performance has varied widely, these evaluations support the finding that federal energy R&D investments have yielded, on the whole, substantial direct economic benefits as well as external benefits such as pollution mitigation and knowledge creation. Government-sponsored energy R&D programs are also commonly thought to have improved substantially since the 1970s and early 1980s, both in terms of the way they are managed and in terms of the objectives they target. More generally, studies of specific technologies and government programs point to the critical role public sector research has played in laying the foundation for technological advances that have later had an enormous impact on the economy (David, Mowery, and Steinmuller 1992), and quantitative estimates suggest the rate of return to publicly funded research is on the order of 20–40 percent. (Note that these figures are not energy specific; see Cockburn and Henderson 2001; as well as Adams 1990; Griliches 1995; Mansfield 1991; and Salter and Martin 2001.)

Recommendations for strengthening the organization, management, and priorities of federal energy R&D efforts emerge from every recent major study of these activities (Chow and Newell 2004; National Commission on Energy Policy 2004).[42] Headway has been made at DOE along several of these lines, and a number of provisions in the Energy Policy Act of 2005 codify recent trends in research management, including nonfederal cost sharing for projects, increased merit review and competitive award of proposals, external technical review of departmental programs, and improved coordination and management of programs.[43] Increased resources should come with diligence toward further improvement.

Particularly in the context of increased funding for strategic basic research, perhaps the most important recommendation is to improve processes for communication, coordination, and collaboration within DOE among the basic research programs in the Office of Science and the applied energy research "stovepipes" within the DOE program offices (fossil fuel, nuclear, renewables, end-use efficiency). The type of process described above for identifying basic research needs is one means to increase such communication, and to better align strategic basic research priorities with applied R&D needs. Such coordination should also extend to ongoing implementation of research priorities in an integrated fashion, including through administrative mechanisms for closer collaboration, development, and evaluation of research-funding initiatives.

Continued use of an interoffice and interagency coordinating body, akin to the current Climate Change Technology Program, will be essential to improve coordination within DOE and between DOE and other agencies with roles related to climate mitigation technology innovation, domestically and internationally (see lower right of Figure 8). While the focus here has been on the DOE R&D programs (because they make up at least 90 percent of the relevant federal R&D), other agencies (e.g., NASA, EPA, DOD, USDA, NSF, DOT, and DOC) have relevant research programs and will be better suited to tackling certain climate mitigation R&D needs. A regularized process for strategic planning, implementation, and evaluation of climate mitigation R&D, including more systematic analysis and oversight of the portfolio as a whole, is an essential means to a more balanced, integrated, and effective R&D program.[44]

41. For example, see Chow and Newell (2004) and NRC (2001) for reviews of several studies. See Jaffe and Lerner (2001) for an evaluation of national laboratory experience with technology commercialization, including an overview of assessments of the DOE labs.
42. In addition to the issues identified below, recommendations also often mention the need for increased cultivation of partnerships linking firms, national laboratories, and universities, as well as finding ways to reduce the impacts of congressional earmarking, micromanagement, and frequent shifts in budget levels and directions.
43. See DOE (1999) for an assessment of DOE's use of merit reviews.
44. This includes more regularized use of planning, investment, and evaluation tools such as those developed in the context of recent NRC studies and associated DOE efforts to measure the prospective and retrospective benefits of applied energy R&D (NRC 2001, 2005, 2007b).

The Energy Policy Act of 2005 also designated an Under Secretary for Science who, in addition to overseeing the Office of Science and its basic science research programs, also is to serve as the Science and Technology Advisor to the Secretary of Energy and has general responsibility to monitor and advise the Secretary of Energy on R&D programs across the department, including supervision and support of research activities in the program offices. The extent and nature of coordinated R&D oversight across the numerous DOE offices that are most relevant to climate mitigation R&D requires ongoing clarification, however, given that these offices currently report to different assistant secretaries and undersecretaries.

In practice, good management, coordination, and ultimately the success of these programs is going to depend heavily on how high a priority is placed on them by future administrations, the individuals appointed to important management roles, and the specific strategies employed. As firms respond by increasing their own innovative efforts in response to increased financial incentives for GHG reduction, it will be increasingly important for public funding agencies to monitor these private research activities and coordinate their research priorities to maximize synergies and avoid duplication. Active scientific and technical advisory committees, including industry participants, are one means of achieving this end.

5.4. Innovation Inducement Prizes for Climate Mitigation Would Broaden the Set of Available Tools and Innovators

Alongside our system of patents and intellectual property rights, three primary mechanisms exist for encouraging R&D: (1) research contracts and grants; (2) research tax credits for the private sector; and (3) innovation inducement prizes.[45] Contracts and grants issued by the DOE and NSF for research performed at the national labs or by universities, other nonprofit institutions, and private firms represent by far the most important policy mechanism currently used to deliver federal support for energy R&D. Recently, attention has turned to innovation-inducement prizes or awards as another possible mechanism for delivering R&D incentives. The idea is to offer financial or other rewards for achieving specific innovation objectives that have been specified in advance (in contrast to ex-post awards like the Nobel Prize; Newell and Wilson 2005; Kalil 2007; NRC 2007a).

Inducement prizes have historically played a role in advancing technology in areas ranging from maritime navigation and canning to mathematics, commercial aviation, and automotive engineering. More recently, in 2004 the $10 million Ansari X-Prize for private space flight became the largest such prize to be awarded. Recent prize proposals relevant to energy and climate policy include "Prizes for Achievement in Grand Challenges of Science and Technology" authorized in the Energy Policy Act of 2005,[46] the H-Prize (for hydrogen) and Bright Tomorrow lighting prizes authorized in the Energy Independence and Security Act of 2007,[47] the privately

45. In addition, important roles exist—within the public and private sectors—for coordination, planning, and road mapping of R&D activities; international cooperation; and general funding for national-level capacity building, including support for education infrastructure.

46. The Energy Policy Act of 2005 (PL 109-58, §1008) authorizes the secretary of the DOE to "carry out a program to award cash prizes in recognition of breakthrough achievements in research, development, demonstration, and commercial application that have the potential for application to the performance of the mission of the Department." It authorizes $10 million for this purpose.

47. The Energy Independence and Security Act of 2007 (PL 110-140, §654) calls for the secretary to "carry out a program to competitively award cash prizes . . . to advance the research, development, demonstration, and commercial application of hydrogen energy technologies." Section 655 calls for the establishment within a year for three different prizes for the development of solid-state lighting packages to replace currently used lights: a 60-Watt Incandescent Replacement Lamp Prize of $10 million, a PAR Type 38 Halogen Replacement Lamp Prize of $5 million, and a Twenty-first Century Lamp Prize of $5 million.

funded Progressive Automotive X-Prize,[48] and the Earth Challenge Prize announced by British financier Richard Branson.[49] Only the last two of these have actually been funded and are under way.

A National Academy Committee recently endorsed the idea of establishing a program of innovation inducement prizes at the NSF—an idea for which Congress has expressed interest—and the America Competes Act gave NSF explicit authority to receive private donations for this purpose.[50] The Reward Innovation in America Act (S. 1371), introduced in 2007, would establish a National Innovation Prizes Board to develop and administer prizes in a range of areas. The prize approach has also been explicitly endorsed in some proposals as an instrument to be used by ARPA-E, were ARPA-E to be funded. Prize-like approaches have also gained traction within the private sector in the form of firms like Innocentive that match *seekers* (organizations with challenging problems) with *solvers* (innovators with solutions) by offering the latter cash awards. Successful solvers often come from fields that are distant from seekers' fields; the more diverse the problem-solving population, the more likely a problem is to be solved.[51] Among other things, Innocentive has a philanthropic subprogram devoted to clean tech and renewable energy, offering prizes supported by a private foundation.

Inducement prizes are clearly not suited to all research and innovation objectives, but they have the potential to play a larger role along with other innovation policy instruments such as research contracts, grants, and R&D tax credits. In contrast to these other instruments, prizes have the attractive incentive property of targeting and rewarding innovation outputs, rather than inputs: the prize is paid only if the objective is attained. This can help encourage maximal research effort per dollar of public research funding. Prizes or awards can also help to focus efforts on specific high-priority objectives, without specifying how the goal is to be accomplished. Because prize competitors select themselves based on their own knowledge of their likelihood of success—rather than being selected in advance by a research manager—prizes can also attract a more diverse and potentially effective range of innovators from the private sector (e.g., industry or individual entrepreneurs), universities, and other research institutions.[52] Hybrid approaches coupling a limited number of competitive R&D contracts for efforts to win a prize should also be considered to more effectively attract competitors from traditional research institutions, where individuals operate principally under a financial model requiring advance commitments for R&D effort.[53]

Rather than wait for Congress to predetermine what specific innovations will be targeted by inducement prizes, the DOE and other appropriate agencies should embrace the approach and undertake a systematic assessment of what specific technical and scientific challenges in GHG mitigation could fruitfully be addressed through a prize approach, as well as the best institutional arrangements for doing so. The most challenging tasks in designing a prize are selecting appropriate prize topics and crafting rules governing the type of contest, size of award, and criteria and methods for determining the

48. The specific targets of the $10 million Progressive Automotive X-Prize competition are fuel economy of at least 100 MPG equivalent; total well-to-wheels GHG emissions of less than 200 grams per mile (CO2 equivalent); criteria pollutants no worse than US EPA Tier II, Bin 5 requirements; GHG emissions from production no worse than typical production of vehicles today; production capability; and other factors such as safety, cost, and features. See http://www.progressiveautoxprize.org/.
49. The Virgin Earth Challenge was launched September 2, 2007, promising a prize of $25 million to whoever can demonstrate to the judges' satisfaction a "commercially viable design which results in the removal of anthropogenic, atmospheric greenhouse gases so as to contribute materially to the stability of the Earth's climate" (http://www.virginearth.com/).
50. This effort would be launched as an experimental program in close consultation with the academic and nonprofit community, technical societies, and industry.
51. See Lakhani and Jeppesen (2007) for a discussion of Innocentive's approach.
52. Conversely, the traditional grants process often relies on the expertise of potential grantees to propose not only a technical approach, but also the specific technical objectives. Thus, the demands on the granting agency in designing a prize can be higher than the traditional grants process, although the ability to target specific objectives is also higher.
53. Some procurement and R&D processes follow a related approach, where funding may be given for the development of proposals to compete for an ultimate contract.

winner (NRC 2007a). Doing so requires extensive consultation with experts and potential participants to ensure the prize goals relate to important societal needs and opportunities, embody a significant yet achievable advance, are clear and understandable to prospective participants, and are stated in an objective, unambiguous way to avoid any doubt as to whether a particular advance would qualify as the winner (NRC 2007a).

DOE (and possibly other relevant agencies) should launch an experimental series of prizes over the next several years employing a small fraction of the additional funds recommended elsewhere in this strategy, or about $200 million in an initial phase, with additional funds thereafter in accordance with an evaluation of the first phase. Prizes could be designed to advance achievements both on the more basic as well as the applied end of the research spectrum. The recent NAS report on inducement prizes provides very useful guidance for development of such a program, which should involve all the DOE research offices. It may make sense for DOE to contract out part of the administration of a prize program, use different management strategies for different prizes, or make prize management a focus of ARPA-E (if ARPA-E comes into being). Assets outside of DOE for specific inducement prizes include deep knowledge of particular technical domains and research communities, as well as expertise in advertising, marketing, and branding.

DOE should also consider designing prizes in the form of, or supplemented by, procurement contracts for equipment that the government otherwise needs to purchase, but that would be required to meet advanced technical and cost criteria. This is one means of incorporating economic cost considerations into the design of prizes, which is otherwise quite difficult. Prize design involving procurement would need to be developed in close coordination with the General Services Administration and Office of Federal Procurement Policy. Finally, inducement prizes could offer a productive means of promoting joint international funding of climate mitigation R&D, and inducing innovations relevant to a developing country context, without preordaining the country in which or specific means by which the prize objectives would be met (Newell 2008). These prize design and management considerations are important and require further detailed development, but should not stand in the way of program establishment.

6. Avoiding Mistakes and Concluding Remarks

The purpose of this innovation strategy is to outline how a well-targeted set of climate policies, including those targeted directly at science and innovation, could help lower the overall costs of mitigation. It is important to stress, however, that poorly designed technology policy will *raise* rather than *lower* the societal costs of climate mitigation. To avoid this, policy should create substantial incentives in the form of a market-based price on GHG emissions, and directed government technology support should emphasize areas least likely to be undertaken by a private sector. As discussed, this would tend to emphasize strategic basic research that advances science in areas critical to climate mitigation. In addition to generating new knowledge and useful tools, such funding also serves the critical function of training the next generation of scientists and engineers for future work in the private sector, at universities, and in other research institutions.

Climate technology policy must complement rather than try to substitute for emissions pricing. On the research side, R&D without market demand for the results is like pushing on a rope, and would ultimately have little impact. On the deployment side, technology-specific mandates and subsidies will tend to generate emissions reductions in a relatively expensive, inefficient way relative to an emissions price, and under an economywide cap-and-trade system will not actually generate any additional reductions. The scale of the climate technology problem and our other energy challenges requires a solution that maximizes the impact of the scarce resources available for addressing these and other critical societal goals. An emissions price plus R&D approach provides the basic framework for such a solution.

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