U.S. Energy Research and Development: Declining Investment, Increasing Need, and the Feasibility of Expansion

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Abstract

Investment in energy research and development in the U.S. is declining despite calls for an enhancement of the nation's capacity for innovation to address environmental, geopolitical, and macro-economic concerns. I examine investments in research and development in the energy sector, and observe broad-based declines in funding since the mid-1990s. The large reductions in investment by the private sector should be a particular area of concern for policy makers. Multiple measures of patenting activity reveal widespread declines in innovative activity that are correlated with R&D investment—notably in the environmentally significant wind and solar areas. Trends in venture capital investment and fuel cell innovation are two promising cases that run counter to the overall trends in the sector. I draw on prior work on the optimal level of energy R&D to identify a range of values which would be adequate to address energy-related concerns. Comparing simple scenarios based on this range to past public R&D programs and industry investment data indicates that a five to ten-fold increase in energy R&D investment is both warranted and feasible.

1 Introduction

Investment in innovation in the U.S. energy sector is declining just as concerns about the environmental, geopolitical, and macroeconomic impacts of energy production and use are intensifying. With energy the largest industry on the planet, having sales of over \$2 trillion annually, investment decisions in this sector have global consequences. The challenges of renewing the U.S. energy infrastructure to enhance economic and geopolitical security (Cheney, 2001) and prevent global climate change (Kennedy, 2004) are particularly acute, and depend on the improvement of existing technologies as well as the invention, development, commercial adoption of emerging ones. Meeting these challenges also depends on the availability of tools to both effectively manage current energy technology investments, and to permit analysis of the most effective approaches and programs to significantly expand our resource of new energy technologies.

The federal government allocates over \$100b annually for research and development (R&D) and considers it a vital "investment in the future" Colwell (2000). Estimates of the percent of overall economic growth that stems from innovation in science and technology are as high as 90% (Mansfield, 1972; Evenson et al., 1979; Griliches, 1987; Solow, 2000). The low investment and large challenges associated with the energy sector however, have led numerous expert groups to call for major new commitments to energy R&D. A 1997 report from the President's Committee of Advisors on Science and Technology and a 2004 report from the bipartisan National Commission on Energy Policy each recommended doubling federal R&D spending

(PCAST, 1997; Holdren et al., 2004). The importance of energy has led several groups to call for much larger commitments (Schock et al., 1999; Davis and Owens, 2003), some on the scale of the Apollo Project of the 1960s (Hendricks, 2004). These recommendations build on other studies in the 1990s that warned of low and declining investment in energy sector R&D (Dooley, 1998; Morgan and Tierney, 1998; Margolis and Kammen, 1999a). The scale of the energy economy, and the diversity of potentially critical low-carbon technologies to address climate change all argue for a set of policies to energize both the public and private sectors (Branscomb, 1993; Stokes, 1997), as well as strategies to catalyze productive interactions between them (Mowery, 1998a,b) in all stages of the innovation process.

These concerns however lie in stark contrast with recent funding developments. Although the Bush administration lists energy research as a "high-priority national need" (Marburger, 2004) and points to the energy bill passed in the summer of 2005 as evidence of action, the 2005 federal budget reduced energy R&D by 11 percent from 2004 (AAAS, 2004b). The American Association for the Advancement of Science projects a decline in federal energy R&D of 18 percent by 2009 (AAAS, 2004a). Meanwhile, and arguably most troubling, the lack of vision on energy is damaging the business environment for existing and start-up energy companies. Investments in energy R&D by U.S. companies fell by 50 percent between 1991 and 2003. This rapid decline is especially disturbing because commercial development is arguably the critical step to turn laboratory research into economically viable technologies and practices.[1] In either an era of declin-

[1]See the 'valley of death' discussion in PCAST, "Report to the President on Federal

ing energy budgets, or in a scenario where economic or environmental needs justify a significant increase in investments in energy research, quantitative assessment tools, such as those developed and utilized here, are needed.

This study consists of three parts: analysis of R&D investment data, development of indicators of innovative activity, and assessment of the feasibility of expanding to much larger levels of R&D. We compiled time-series records of investments in U.S. energy R&D (Figure 1) (Jefferson, 2001; Meeks, 2004; Wolfe, 2004a,b). Complementing the data on public sector expenditures, we developed and make available here a database of private sector R&D investments for fossil fuels, nuclear, renewables, and other energy technologies.[2] In addition, we use U.S. patent classifications to evaluate the innovation resulting from R&D investment in five emerging energy technologies. We develop three methods for using patents to assess the effectiveness of this investment: patenting intensity, highly-cited patents, and citations per patent. Finally, we compile historical data on federal R&D programs and then assess the economic effects of a large energy R&D program relative to those.

Energy Research and Development for the Challenges of the Twenty-First Century" (Office of the President, 1997), section 7-15 (PCAST, 1997).

[2]Data is available at `http://ist-socrates.berkeley.edu/~gnemet/RandD2006.html`. It is also provided here in the attached appendix.

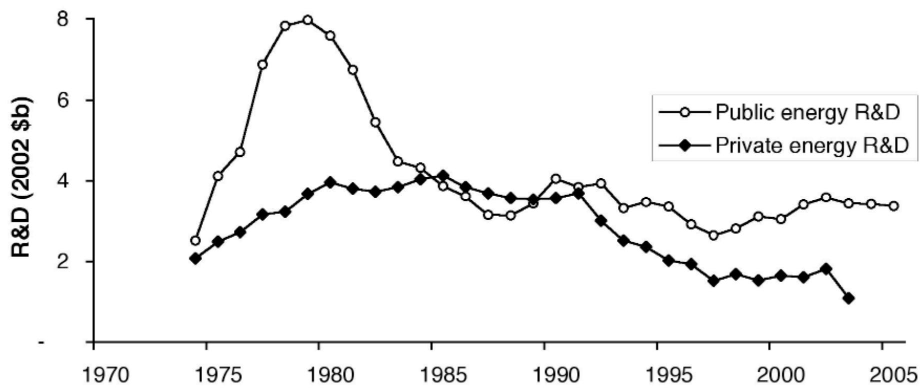

Figure 1: Energy R&D investment by public and private sectors.
The percentage of total R&D in the U.S. invested in energy technology has fallen from 10% to 2%. These time series are derived from federal budgets and from surveys of companies conducted by the National Science Foundation (Jefferson, 2001; Meeks, 2004; Wolfe, 2004a,b).

2 Declining R&D investment throughout the energy sector

The U.S. invests about $1 billion less in energy R&D today than it did a decade ago. This trend is remarkable, first because the levels in the mid-1990s had already been identified as dangerously low (Margolis and Kammen, 1999b), and second because, as our analysis indicates[3], the decline is pervasive—across almost every energy technology category, in both the public and private sectors, and at multiple stages in the innovation process, investment has been either been stagnant or declining (Figure 2). More-

[3]We disaggregate energy R&D into its four major components: fossil fuels, nuclear power, renewables and energy efficiency, and other energy technologies (such as environmental programs). While public spending can be disaggregated into more precise technological categories, this level is used to provide consistent comparisons between the private and public sectors. For individual years in which firm-level data is kept confidential, averages of adjacent years are used.

over, the decline in investment in energy has occurred while overall U.S. R&D has grown by 6% per year, and federal R&D investments in health and defence have grown by 10 to 15% per year, respectively (Figure 3). As a result, the percentage of all U.S. R&D invested in the energy sector has declined from 10% in the 1980s to 2% today (Figure 4). Private sector investment activity is a key area for concern. While in the 1980s and 1990s, the private and public sectors each accounted for approximately half of the nations investment in energy R&D, today the private sector makes up only 24%. The recent decline in private sector funding for energy R&D is particularly troubling because it has historically exhibited less volatility than public funding—private funding rose only moderately in the 1970s and was stable in the 1980s; periods during which federal funding increased by a factor of three and then dropped by half. The lack of industry investment in each technology area strongly suggests that the public sector needs to play a role in not only increasing investment directly but also correcting the market and regulatory obstacles that discourage investment in new technology (Duke and Kammen, 1999). The reduced inventive activity in energy reaches back even to the earliest stages of the innovation process, in universities where fundamental research and training of new scientists occurs. For example, a recent study of federal support for university research raised concerns about funding for energy and the environment as they found that funding to universities is increasingly concentrated in the life sciences (Fossum et al., 2004).

A glimpse at the drivers behind investment trends in three segments of the energy economy indicates that a variety of mechanisms are at work.

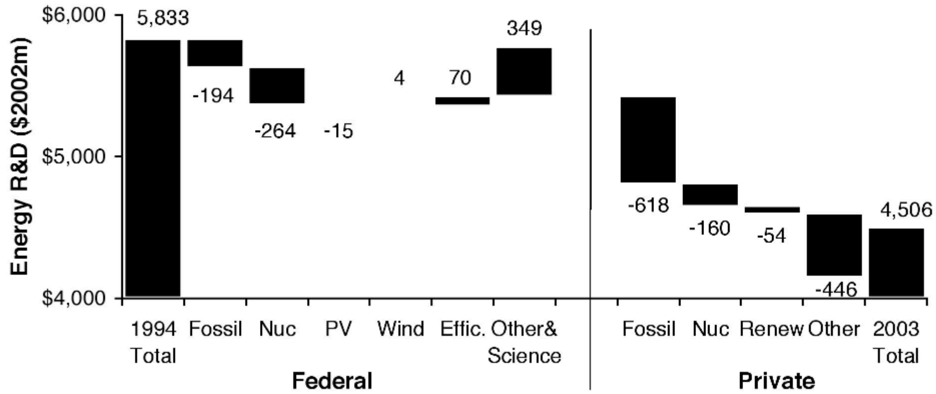

Figure 2: Changes in energy R&D investment by sector and technology 1994-2003.
The total change in R&D investment between 1994 and 2003 is disaggregated according to the contribution of each technology category and each sector. For example, of the $1,327m reduction in total energy R&D investment from 1994 to 2003, $618m was due to the decline in fossil fuel funding by the private sector.

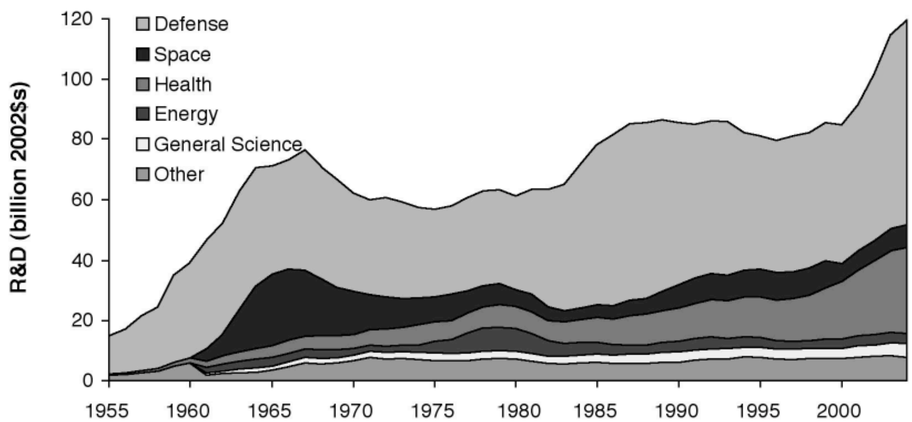

Figure 3: Federal R&D 1955 to 2004.
Annual level of R&D funding by federal agency.

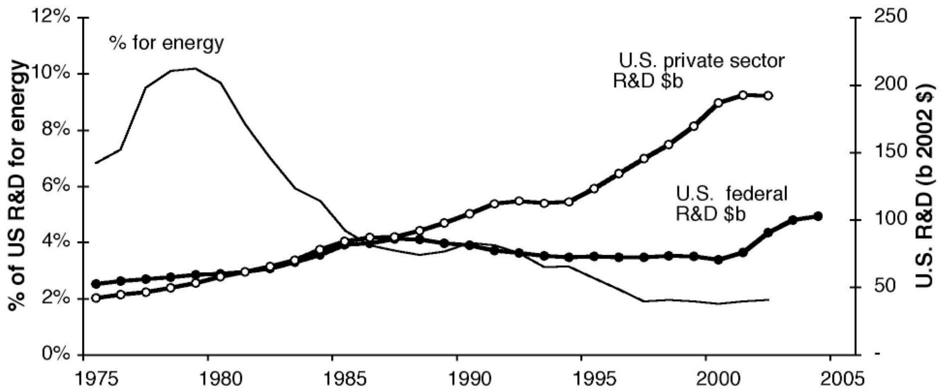

Figure 4: Total U.S. R&D and percentage devoted to energy.
Lines with circles indicate R&D investment levels in the U.S for all sectors. White circles show investment by companies and black circles federal government investment. Solid line indicates energy R&D spending as a percentage of total U.S. R&D spending.

First, the market for fossil fuel electricity generation has been growing by 2 to 3% per year and yet R&D has declined by half in the past 10 years, from $1.5b to $0.7b. In this case, the shift to a deregulated market has been an influential factor reducing incentives for collaboration, and generating persistent regulatory uncertainty. The industry research consortium, the Electric Power Research Institute (EPRI), has seen its budget decline by a factor of three. Rather than shifting their EPRI contributions to their own proprietary research programs, investor-owned utilities and equipment makers have reduced both their EPRI dues and their own research programs. The data on private sector fossil R&D validate Dooley's prescient warnings in the mid-1990s (Dooley, 1998) about the effect of electricity sector deregulation on technology investment. Second, the decline in private sector nuclear R&D corresponds with diminishing expectations about the future construction of new plants. Over 90% of nuclear energy R&D is now federally funded. This lack of a "demand pull" incentive has persisted for so long that it even affects interest by the next generation nuclear workforce; enrolment in graduate-level nuclear engineering programs has declined by 26% in the last decade (Kammen, 2003). Recent interest in new nuclear construction has so far not translated into renewed private sector technology investment. Third, policy intermittency and uncertainty plays a role in discouraging R&D investments in the solar and wind energy sectors which have been growing by 20 to 35% per year for more than a decade. Improvements in technology have made wind power competitive with natural gas (Jacobson and Masters, 2001) and have helped the global photovoltaic industry to expand by 50% in 2004 (Maycock, 2005). Yet, investment by large companies in developing these rapidly expanding technologies has actually declined. By contrast, European and Japanese firms are investing and growing market share in this rapidly growing sector making the U.S. increasingly an importer of renewables technology.

Venture capital investment in energy provides a potentially promising exception to the trends in private and public R&D. Energy investments funded by venture capital firms in the U.S. exceeded one billion dollars in 2000, and despite their subsequent cyclical decline to $520m in 2004, are still of the same scale as private R&D by large companies (Figure 5) (Prudencio, 2005). Recent announcements, such as California's plan to devote up to $450m of its public pension fund investments to environmental technology companies and Pacific Gas and Electric's $30m California Clean Energy Fund for funding new ventures suggest that a new investment cycle may be

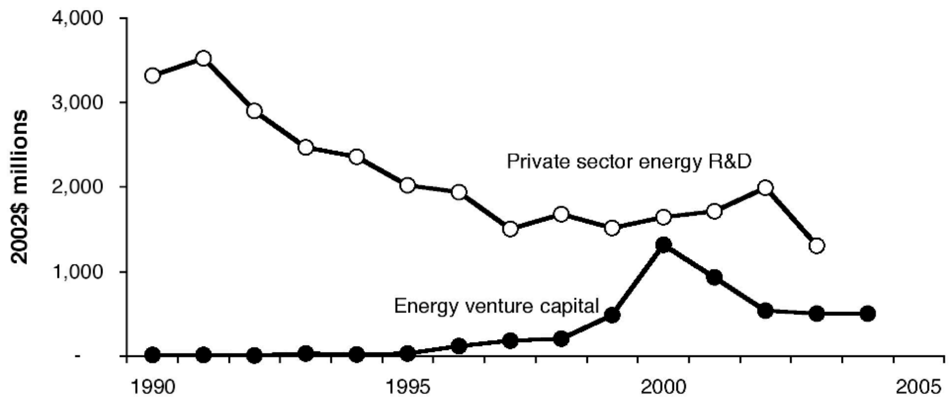

Figure 5: U.S. Venture capital investments in energy and private sector energy R&D.
Funding by companies (less than 500 employees) is compared to investment in emerging companies by venture capital firms.

starting (Angelides, 2004). The emergence of this new funding mechanism is especially important because studies have found that in general, venture capital investment is 3 to 4 times more effective than R&D at stimulating patenting Kortum and Lerner (2000). While it does not offset the declining investment by the federal government and large companies, the venture capital sector is now a significant component of the U.S. energy innovation system, raising the importance of monitoring its activity level, composition of portfolio firms, and effectiveness in bringing nascent technologies to the commercial market.

Finally, the drugs and biotechnology industry provides a revealing contrast to the trends seen in energy. Innovation in that sector has been broad, rapid and consistent. The 5,000 firms in the industry signed 10,000 technology agreements during the 1990s, and the sector added over 100,000 new jobs in the last 15 years (Cortwright and Meyer, 2002). Expectations of future benefits are high—the typical biotech firm spends more on R&D ($8.4 million) than it receives in revenues ($2.5 million), with the difference generally funded by larger firms and venture capital (PriceWaterhouseCoopers, 2001). Although energy R&D exceeded that of the biotechnology industry 20 years ago, today R&D investment by biotechnology firms is an order of magnitude larger than that of energy firms (Figure 6). In the mid-1980s, U.S. companies in the energy sector were investing more in R&D ($4.0 billion) than were drug and biotechnology firms ($3.4 billion), but by 2000, drug and biotech companies had increased their investment by almost a factor of 4 to $13 billion. Meanwhile, energy companies had cut their investments by more than half to $1.6 billion. From 1980 to 2000, the energy sector invested $64 billion in R&D while the drug and biotech sector invested $173b. Today, total private sector energy R&D is less than the R&D budgets of individual biotech companies such as Amgen and Genentech.

3 Reductions in patenting intensity

Divergence in investment levels between the energy and other sectors of the economy is only one of several indicators of under-performance in the energy economy. In this section we present results of three methods developed to assess patenting activity, which earlier work has found to provides an indication of the outcomes of the innovation process (Griliches, 1990).

First, we use records of successful U.S. patent applications as a proxy for the intensity of inventive activity and find strong correlations between

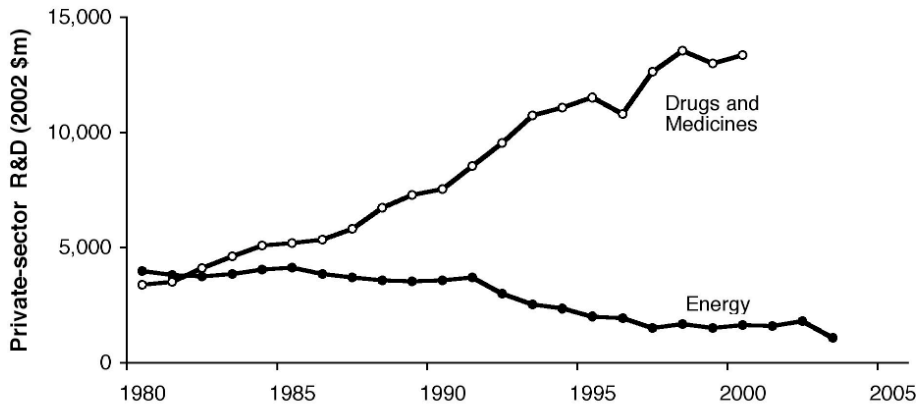

Figure 6: Private-sector R&D investment: energy vs. drugs and medicines. R&D investment by companies in the energy sector is compared to investment by those in the drugs and medicines sector.

public R&D and patenting across a variety of energy technologies (Figure 7).[4] Since the early-1980s all three indicators—public sector R&D, private sector R&D, and patenting—have exhibited consistently negative trends.[5] Public R&D and patenting are highly correlated for wind, PV, fuel cells, and nuclear fusion. Nuclear fission is the one category that is not well correlated to R&D. Comparing patenting against private sector R&D for the more aggregated technology categories also reveals concurrent negative trends.[6] The long-term decline in patenting across technology categories and their correlation with R&D funding levels provide further evidence that the technical improvements upon which performance-improving and cost-reducing innovations are based are occurring with decreasing frequency.

[4]Patents data were downloaded from the U.S. Patent and Trademark Office, "US Patent Bibliographic Database" `www.uspto.gov/patft/` (2004).

[5]From 1980 to 2003, public R&D declined by 54%, private R&D by 67%, and patenting by 47%.

[6]While the general correlation holds here as well, the abbreviated time-series (1985-2002) and the constant negative trend reduce the significance of the results.

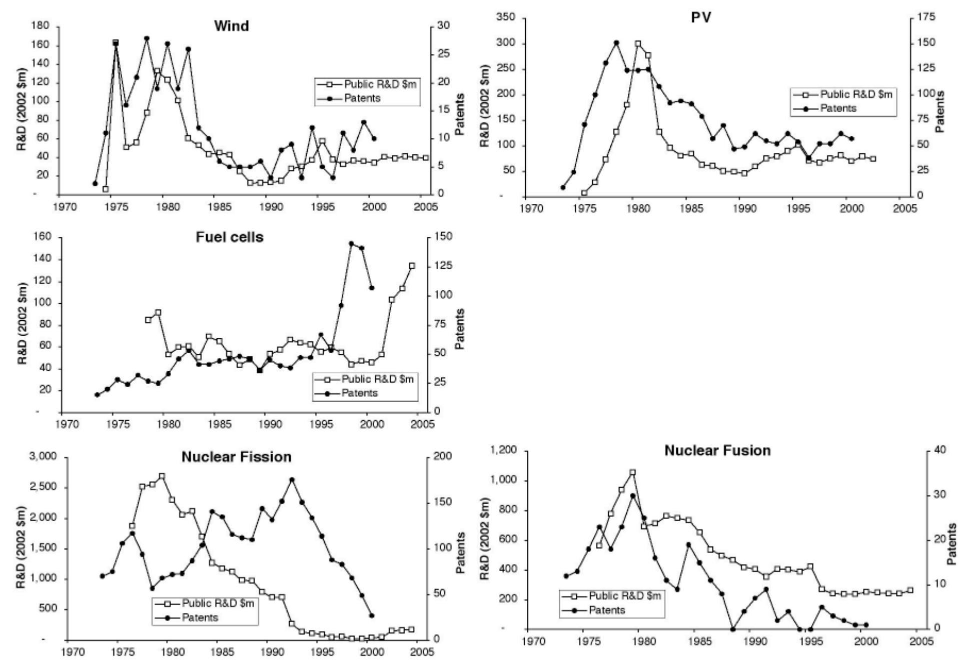

Figure 7: Patenting and federal R&D.
Patenting is strongly correlated with federal R&D. To provide comparisons with U.S. R&D funding, foreign patents are excluded. The data include granted patents in the U.S. patent system filed by U.S. inventors only. Patents are dated by their year of application to remove the effects of the lag between application and approval. This lag averages two years.

Second, in the same way that studies measure scientific importance using journal citations (May, 1997), patent citation data can be used to identify "high-value" patents (Harhoff et al., 1999). For each patent we identify the number of times it is cited by subsequent patents using the NBER Patent Citations Datafile (Hall et al., 2001). For each year and technology category, we calculate the probability of a patent being cited by recording the number of patents in that technology category in the next 15 years. We then calculate the adjusted patent citations for each year using a base year. "High-value" patents are those that received twice as many citations as the average patent in that technology category. Between 5 and 10% of the patents we looked at fell under our definition of high-value. The Department of Energy accounts for a large fraction of the most highly cited patents, with a direct interest in 24% (6 of the 25) of the most frequently referenced U.S. energy patents, while only associated with 7% of total U.S. energy patents. In the energy sector, valuable patents do not occur randomlythey cluster in specific periods of productive innovation (Figure 8).[7] The drivers behind these clusters of valuable patents include R&D investment, growth in demand, and exploitation of technical opportunities. These clusters both reflect successful innovations, productive public policies, and mark opportunities to further energize emerging technologies and industries.

Third, patent citations can be used to measure both the return on R&D investment and the health of the technology commercialization process, as patents from government research provide the basis for subsequent patents related to technology development and marketable products. The difference

[7] Analysis based on the citation weighting methodology of Dahlin et al. (2004).

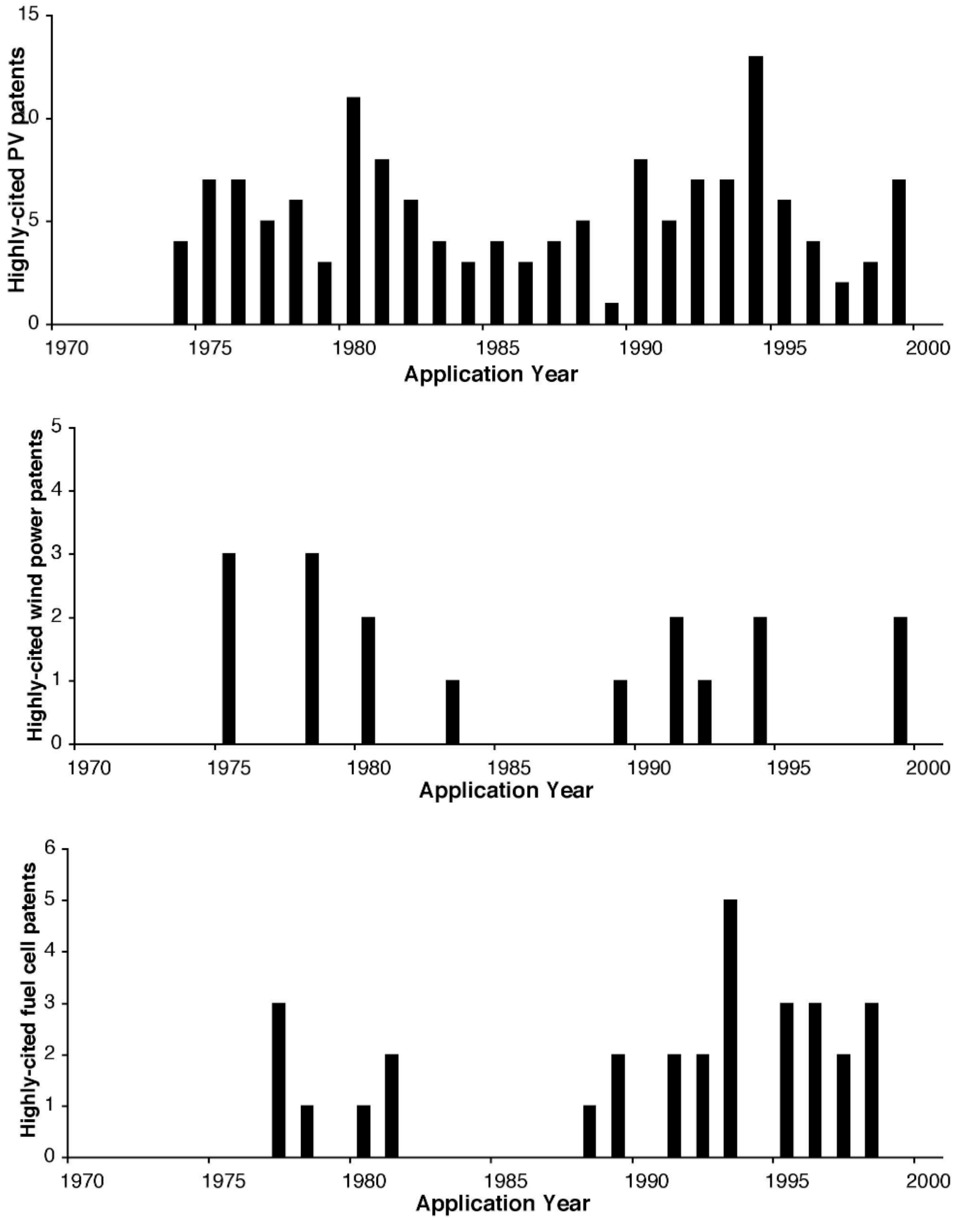

Figure 8: Highly-cited patents.
For each patent the number of times it is cited by subsequent patents is calculated. “High-value” patents are those that received twice as many citations as the average patent in that technology category. Between 5 and 10% of the patents examined qualified as high-value.

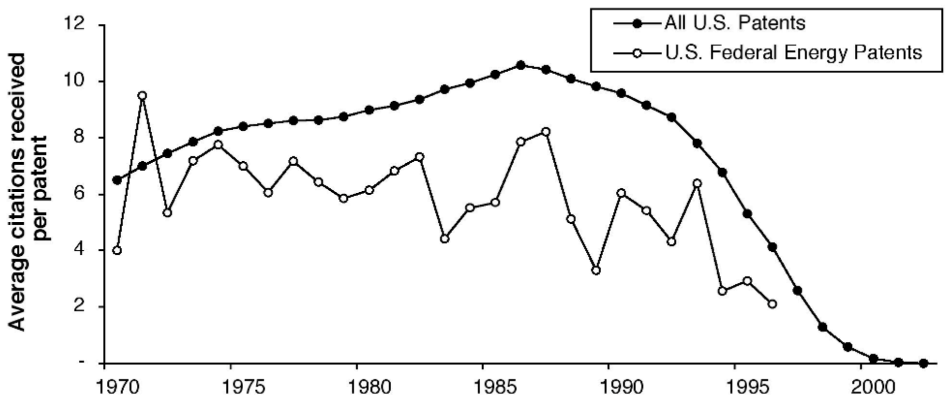

Figure 9: Average patent citations received per patent granted.
The y-axis indicates the average number of times a patent was cited by subsequent patents. The average of all patents filed during the year is shown on the x-axis. Recent patents, those issued within the past five years, were omitted because there has been insufficient time for them to accrue a citation history. In each decade, the average energy patent received fewer citations than the suite of all U.S. patents: 6.6 vs. 8.0 in the 1970s, 6.1 vs. 9.8 in the 1980s, and 4.3 vs. 7.4 in the 1990s. In aggregate, between 1970 and 2000 patents in the energy sector received one third fewer citations than did those across all fields.

between the U.S. federal energy patent portfolio and all other U.S. patents is striking, with energy patents earning on average only 68 percent as many citations as the overall U.S. average from 1970 to 1997 (Figure 9). This lack of development of government-sponsored inventions should not be surprising given the declining emphasis on innovation among private energy companies.

In contrast to the rest of the energy sector investment and innovation in fuel cells have grown. Despite a 17% drop in federal funding, patenting activity intensified by nearly an order of magnitude, from 47 in 1994 to 349 in 2001. Trends in patenting and the stock prices of the major firms in the industry reveal a strong correlation between access to capital and the rate of innovation (Figure 10). The relationship between fuel cell company stock prices and patenting is stronger than that between patenting and public R&D. The five firms shown account for 24 percent of patents from 1999 to 2004. Almost 300 firms received fuel cell patents between 1999 and 2004, reflecting participation both by small and large firms. This combination of increasing investment and innovation is unique within the energy sector. While investments have decreased as venture funding overall has receded since the late 1990s, the rapid innovation in this period industry has provided a large new stock of knowledge on which new designs, new products, and cost-reducing improvements can build. The industry structure even resembles that of the biotechnology industry. A large number of entrepreneurial firms and a few large firms collaborate through partnerships and intellectual property licensing to develop this earlier stage technology (Mowery, 1998b). The federal government, therefore, need not be the only driver of innovation in the energy sector if private sector mechanisms and business opportunities are robust.

4 Could energy R&D be dramatically increased?

In light of this record, how feasible would it be to raise investment to levels commensurate with the energy-related challenges we face? Here we rely on earlier work to arrive at a range of plausible scenarios for optimal levels of energy R&D and then gauge the feasibility of such a project using historical data

Calls for major new commitments to energy R&D have become common—

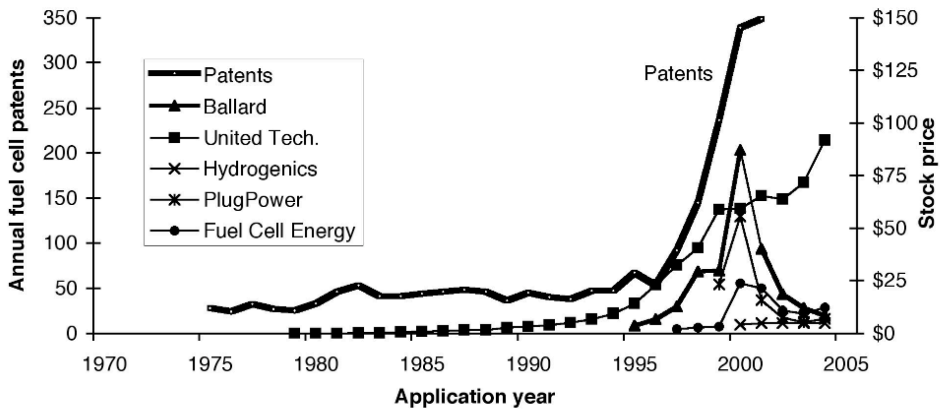

Figure 10: Fuel cell patenting and stock prices.
The relationship between fuel cell company stock prices and patenting is stronger than that between patenting and public R&D. The five firms shown account for 24% of patents from 1999 to 2004. 288 firms received fuel cell patents between 1999-2004.

while both the PCAST study of 1997 (PCAST, 1997) and the 2004 NCEP report (Holdren et al., 2004) recommend doubling federal energy R&D, others have found that larger increases are warranted. Davis and Owens (2003) found that the option value of energy R&D justifies increasing spending to four times the present level. Schock et al. (1999) valued energy R&D by providing estimates of the insurance needed against oil price shocks, electricity supply disruptions, local air pollution, and climate change. By estimating the magnitude of the risks in each area and the probabilities of energy R&D programs to reduce them, they found that increasing energy R&D by a factor of four would be a 'conservative' estimate of its insurance value. We note that this estimate assumes a mean climate stabilization target of between 650 and 750 ppm CO_2 and incorporates a 35% probability that no stabilization at all will be needed. A recalculation of their model to target the

560-ppm atmospheric level, scenario A1T ('rapid technological change') of the Intergovernmental Panel on Climate Change (Nakicenovic et al., 2000), increases the optimal R&D investment in energy R&D to $17 to $27 billion, 6 to 9 times the current level of investment. Uncertainty in the optimal level is indeed large. To incorporate the range of these estimates, we develop two scenarios for scaling up energy R&D, one for five times the current level and one for ten times.

The performance of previous large-scale R&D programs provides a useful test of the viability of carrying out an energy 'Apollo' or 'Manhattan' project, as these ventures are often termed. We find that a 5- to 10-fold increase in spending from current levels is not a 'pie in the sky' proposal; in fact it is consistent with the growth seen in several previous federal programs, each of which took place in response to clearly articulated national needs. Past experience indicates that this investment would be repaid several times over in technological innovations, business opportunities, and job growth, beyond the already worthy goal of developing a low-carbon economy. We assembled data and reviewed spending patterns of the six previous major federal R&D initiatives since 1940 (Table 1) and use five measures to compare them to scenarios of increasing energy R&D by factors of five and ten. For each of these eight programs we calculate a "baseline" level of spending. The difference between the actual spending and the baseline during the program we call extra program spending. We compare the energy scenarios to the other initiatives using five measures that address both the peak year and the full duration of the program. A 10x expanded energy investment scenario is within the range of the previous programs in all but one

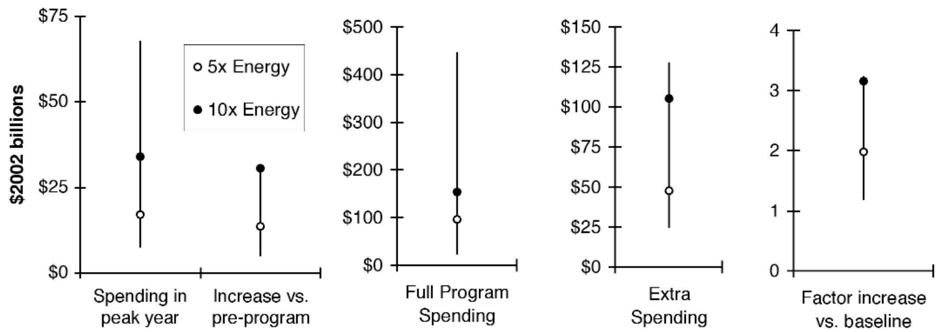

Figure 11: Energy R&D scenarios plotted against the range of previous programs.
For each of the five measures, the vertical line represents the range of values exhibited by the previous large federal R&D programs. The white circle (○) indicates the value for a 5x energy R&D scenario and the black dot (●) for a 10x energy scenario.

measure, where it exceeds by 10%. A 5x energy scenario is in the lower half of the range for each measure. Figure 11 shows the scenarios (as circles) plotted against the range of previous programs. While expanding energy R&D to five or ten times todays level would be a significant initiative, the fiscal magnitude of such a program is well within the range of previous programs, each of which have produced demonstrable economic benefits beyond the direct program objectives.

A critical role for public sector investment has always been to energize and facilitate private sector activity. In fact, increasing energy R&D investment in the private sector by a factor of five or ten would not even rival what is seen in other high-technology sectors. From 1988 to 2003 the U.S. energy industry invested only 0.23% of its revenues in R&D. This compares to the period 1975 to 87 when private sector R&D averaged 1.1%, peaking at

Table 1: Comparison of energy R&D scenarios and major federal government R&D initiatives (2002 $b)

			Peak Year		Program Duration		
Program[a]	Sector	Years	Spending	Increase	Spending	Extra Spending[b]	Factor Increase
Manhattan Project	Defence	1942–45	$10.0	$10.0	$25.0	$25.0	n/a
Apollo Program	Space	1963–72	$23.8	$19.8	$184.6	$127.4	3.2
Project Independence	Energy	1975–82	$7.8	$5.3	$49.9	$25.6	2.1
Reagan defence	Defence	1981–89	$58.4	$27.6	$445.1	$100.3	1.3
Doubling NIH	Health	1999–04	$28.4	$13.3	$138.3	$32.6	1.3
War on Terror	Defence	2002–04	$67.7	$19.5	$187.1	$29.6	1.2
5x energy scenario	Energy	2005–15	$17.1	$13.7	$96.8	$47.9	2.0
10x energy scenario	Energy	2005–15	$34.0	$30.6	$154.3	$105.4	3.2

[a] "Major R&D initiatives" in this study are federal programs in which annual spending either doubled or increased by more than $10 billion during the program lifetime.

[b] For each of these eight programs we calculate a "baseline" level of spending based on the 50-year historical growth rate of U.S. R&D, 4.3% per year. The difference between the actual spending and the baseline during the program we call extraordinary or, "extra", program spending.

1.4% in 1978. Overall R&D in the US economy was 2.6% of GDP over that time and has been increasing. High-tech industries such as pharmaceuticals, software, and computers routinely invest between 5 and 15% of revenues in R&D (MIT, 2002). An order of magnitude increase in R&D investments by the energy industry would still leave the energy sector's R&D intensity below the average of 2.6% for U. S. industry as a whole (BEA, 2004; Wolfe, 2004a). If the electric power industry alone were to devote 2% of revenue to R&D for the next decade, the resulting $50 billion would exceed cumulative energy R&D invested since the 1970s, yet would be smaller than cumulative profits of $168 billion from 1994 to 2003 (Kuhn, 2004) and would be dwarfed by the $1.7 trillion forecast to be spent on new equipment and upgrades in the North American power sector from 2001 to 2030 (Birol, 2003). The confluence of this upcoming capital investment and a federal programmatic initiative and commitment would enable new capacity to make full use of the technologies developed in a research program and would provide opportunities for incorporating market feedback and stimulating learning effects.[8] Given recent investment declines in the private sector, creating an environment in which firms begin to invest at these level will be an important policy challenge.

We also examined the thesis that these large programs "crowd out" other research and using the data described in this study, found that the evidence

[8]It is important to note that this analysis does not suggest that energy utilities should necessarily be asked or expected to make this investment without strong assurance that public sector investment will itself increase, but more critically that these investments will be facilitated by regulation and incentives that reward research into clean energy technologies and practices.

for this contention is weak or nonexistent.[9] In fact, large government R&D initiatives were associated with *higher* levels of both private sector R&D and R&D in other federal programs. The economy-wide effects of such major R&D programs could arguably be either negative or positive. The positive macro effects of R&D accrue from two types of "spillovers": firms do not capture the full value of their innovations (Jones and Williams, 1998) and indirect benefits emerge, such as the 10:1 benefit ratio of the Apollo program (Apollo-Alliance, 2004). Assuming that the value of the direct outcomes of an R&D program exceed investment, the main negative consequence of large R&D programs is that they may crowd out R&D in other sectors by limiting these other sectors access to funding and scientific personnel (Goolsbee, 1998). The R&D data described above can be used to develop a simple model relating these six major federal R&D programs to R&D spending in other areas, both in the public and private sectors. We test two aspects of the crowding-out hypothesis: First, whether large federal programs are associated with reduced spending in *other federal R&D*, and second, whether these programs lead to lower spending in *private sector R&D*. In a model of spending on other federal R&D activities, we controlled for GDP and found that the coefficient for the targeted R&D effort is small, positive, and significant (see Table 2).

We found a similar result in a model explaining private R&D.

Our data on private R&D extend only to 1985, and therefore do not go back far enough to test for significant results. However, a glance at R&D

[9]Our finding is consistent with that of David et al. (2000), a meta-analysis of empirical R&D crowding-out studies that found little evidence of crowding out across a wide array of sectoral and macro-economic studies.

Table 2: The effect of large R&D programs on other R&D investment

Dependent Variable	Independent variables[a]				
Model 1[b]					
ln(otherfedR&D)	ln(programR&D)	ln(GDP)	mean	R^2	n
	0.03*	0.43*	3.35	0.87	31
	(0.01)	(0.03)	(0.06)		
Model 2[c]					
privateR&D	program	GDP	mean	R^2	n
	7.40*	25.8*	-87.2	0.99	28
	(2.31)	(0.60)	(5.22)		

[a]An asterisk indicates that coefficient is significant at the 95% level.
[b]Data Definitions for Model 1:
otherfedR&D: Annual spending on programs other than those being emphasized.
programR&D: Extra-normal annual spending on a *large* government R&D programs.
GDP: Annual level of U.S. Gross Domestic Product.
[c]Data Definitions for Model 2:
privateR&D: Annual U.S. R&D spending by the private sector.
program: Dummy variable for which 1 means a large R&D program was under-way.

trends in both energy and biotech show that private investment rose during periods of large government R&D increases. One interpretation of these results is that the signal of commitment that a large government initiative sends to private investors outweighs any crowding-out effects associated with competition over funding or retention of scientists and engineers. Another is that in these long-term programs, the stock of scientists and engineers is not fixed. Just as the dearth of activity in the nuclear sector has led to decreased enrolment in graduate programs, a large long-term program with a signal of commitment from public leaders can increase the numbers of trained professionals within a few years. These results suggest that the crowding-out effect of previous programs was weak, if it existed at all. Indeed our results indicate the opposite of a crowding-out effect: large government R&D initiatives are associated with higher levels of both private sector R&D and R&D in other federal programs.[10]

5 Conclusion

The decline in energy R&D and innovative activity seen over the past three decades is pervasive and, apparently a continuing trend. While government funding is essential in supporting early stage technologies and sending signals to the market, evidence of private sector investment is an important indicator of expectations about technological possibilities and market potential. The dramatic declines in private sector investment are thus particularly

[10]In current work in progress we are collecting data to explore an alternative measure by looking at the effects on private R&D investment within the sector for which the government is initiating a large program.

concerning if we are to employ an innovation-based strategy to confront the major energy-related challenges society now faces. R&D alone is not sufficient to bring the new energy technologies we will require to widespread adoption. However, the correlations we report demonstrate that R&D is an essential component of a broad innovation-based energy strategy that includes transforming markets and reducing barriers to the commercialization and diffusion of nascent technologies. The evidence we see from past programs indicates that we can effectively scale up energy R&D, without hurting innovation in other sectors of the economy. At the same time, such a large and important project will require the development of additional ways of assessing returns on investments to inform the allocation of support across technologies, sectors, and the multiple stages of the innovation process.

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

This appendix describes the methodology used to arrive at the scenarios for future energy R&D investment of 5- and 10-times current levels, as described in the paper.

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

A recalculation of their model to target the 550-ppm atmospheric level, scenario A1T ('rapid technological change') of the Intergovernmental Panel on Climate Change (Nakicenovic et al., 2000), increases the optimal R&D investment in energy R&D to \$11 to \$32 billion, 3 to 10 times the current level of investment. Figure 12 shows the probability distribution assumed by (Schock et al., 1999) and the target value of 550ppm (vertical dashed line) we use in this analysis.

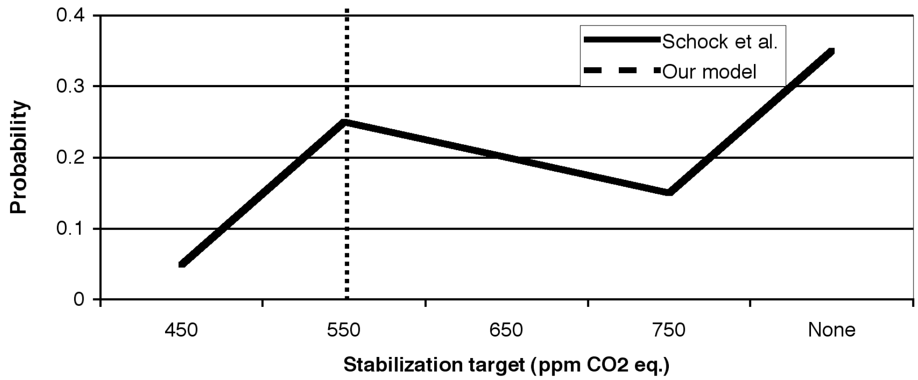

Figure 12: Comparison of probability distribution for climate stabilization used by Schock et al. (1999) with the 550 ppm target used in in our analysis.

A.1 Model Description

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

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

$$V_{US} = A \sum_{i=1}^{5} (S_i P_i L_i) \tag{1}$$

Like Schock et al. (1999), we assume that the contribution to worldwide

R&D by the U.S. (A) is in proportion to its current share of worldwide greenhouse gas emissions, approximately 25%.

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

The probabilities (L) of needing to stabilize at each level i, are used as shown in the figure above. For the Schock et al. (1999) model these are: 0.05 at 450 ppm, 0.25 at 550 ppm, 0.2 at 650 ppm, 0.15 at 750 ppm, and 0.35 for the case of no stabilization. In contrast to the probability density function they use, we select the doubling of pre-industrial levels as our target and thus assign the level i = 550ppm a "probability" of 1.

We use the values developed by Schock et al. (1999) for the assumed probability of R&D success (P). These probabilities decrease with stabilization levels, under the assumption that lower stabilization will require larger contributions from early-stage technologies whose ultimate viability is less likely than near-term options. The range for 550 ppm is 0.5 to 0.8. We use both ends of this range to bound our estimate.

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

$$\mathrm{S_i} = \mathrm{C_i} - \mathrm{CRD_i} \tag{2}$$

We use the costs to stabilize (C) calculated by Schock et al. (1999), who used the MiniCAM 2.0 model applied to two sets of mitigation scenarios, those by Wigley et al. (1996) and the IPCC Nakicenovic et al. (2000). The cost to stabilize at 550 ppm is in the range of $0.9 to $2.4 trillion. It is important to note that these scenarios already include technology improvement, although they do not specify how much R&D is implied to achieve this "autonomous" improvement. As Schock et al. (1999) point out, if any of this assumed improvement depends on higher levels of R&D, the estimates calculated in this model will then underestimate the R&D required.

The costs to stabilize using the outcomes of a successful R&D program (CRD) are lower because the energy technologies developed in the R&D program can be used to offset greenhouse gas emissions at lower costs than using existing technologies. We use the assumption by Schock et al. (1999) that a successful R&D program will enable us to deploy technologies that produce energy at costs similar to business-as-usual costs while reducing emissions sufficient to stabilize at the 550 ppm level.

A.2 Data comparison

Table 3 below shows the values used in the model. In our version of the model we use the same values as Schock et al. (1999) for the 550 ppm level. The one exception is the probabilities assumed for the needing to achieve each stabilization level (L). Our model is conditional on a stabilization target of 550 ppm, because we are deriving the amount of R&D required to achieve a specific target. In contrast, Schock et al. (1999) treat the stabilization level as an uncertain parameter with a known probability density function.

Table 3: Comparison of parameter values used in the models

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

A.3 Outcomes and other risks

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

Finally, we note that in their model, Schock et al. (1999) show that energy R&D can be used as insurance against other risks as well, such as oil price shocks, electricity outages, and air pollution. Using energy R&D to mitigate these risks has an annual value of $9 to $10 billion. The figures above are perhaps overly conservative in that they assume that the R&D programs launched to address climate stabilization perfectly overlap with the programs used to address these other risks. A less conservative estimate would be to assume that perhaps half of the other risks would be addressed by the climate R&D program and half would not. For example, investments to improve the reliability of the electricity grid would reduce damages due to power outages but would not necessarily be included in a large climate R&D program. In that case, optimal energy R&D would rise to $11 to $32 billion per year, or roughly 3 to 10 times current levels. We used this result to devise the scenarios that we use in our paper—5x and 10x energy R&D. We compared investment in these scenarios to that of the large R&D programs of the past.

References

AAAS. Analysis of the outyear projections for R&D in the FY 2005 budget. In *forthcoming in AAAS Report XXIX: Research and Development FY 2005*. AAAS, Washington, DC, 2004a.

AAAS. Nondefense R&D budgets face major squeeze. *Issues in Science and Technology*, 21(1):17–19, 2004b.

Phil Angelides. State treasurer phil angelides launches green wave environmental investment initiative. Technical report, Office of the State Treasurer of California, February 3 2004.

Apollo-Alliance. The Apollo jobs report: Good jobs and energy independence, new energy for America. Report, The Apollo Alliance, January 2004.

BEA. Gross domestic product (GDP) by industry. Technical report, Bureau of Economic Analysis, December 2004.

Fatih Birol. *World Energy Investment Outlook*. International Energy Agency, Paris, 2003.

Lewis M. Branscomb. *Empowering Technology: Implementing a U.S. Strategy*. The MIT Press, Cambridge, MA, 1993.

Richard Cheney. National energy policy. Report, National Energy Policy Development Group, Office of the Vice President, May 16 2001.

Rita R. Colwell. *America's Investment in the Future*. National Science Foundation, Washington, DC, 2000.

Joseph Cortwright and Heike Meyer. Signs of life: The growth of biotechnology centers in the u.s. Report, Brookings, 2002.

Kristina Dahlin, Margaret Taylor, and Mark Fichman. Today's Edisons or weekend hobbyists: Technical merit and success of inventions by independent inventors. *Research Policy*, 33:1167–1183, 2004.

Paul A. David, Bronwyn H. Hall, and Andrew A. Toole. Is public R&D a complement or substitute for private R&D? a review of the econometric evidence. *Research Policy*, 29(4-5):497–529, 2000.

Graham A. Davis and Brandon Owens. Optimizing the level of renewable electric R&D expenditures using real options analysis. *Energy Policy*, 31:1589–1608, 2003.

J.J. Dooley. Unintended consequences: Energy R&D in a deregulated energy market. *Energy Policy*, 26(7):547–555, 1998.

R.D. Duke and D.M. Kammen. The economics of energy market transformation initiatives. *The Energy Journal*, 20(4):15–64, 1999.

Robert E. Evenson, Paul E. Waggoner, and Vernon W. Ruttan. Economic benefits from research: An example from agriculture. *Science*, 205:1101–1107, 1979.

Donna Fossum, Lawrence S. Painter, Elisa Eiseman, Emile Ettedgui, and David M. Adamson. Vital assets: Federal investment in research and development at the nation's universities and colleges. Report, RAND, 2004.

Austan Goolsbee. Does government R&D policy mainly benefit scientists and engineers? *American Economic Review*, 88(2, Papers and Proceedings of the Hundred and Tenth Annual Meeting of the American Economic Association):298–302, 1998. Tax and Human-Capital Policy Papers and Proceedings of the Hundred and Tenth Annual Meeting of the American Economic Association 00028282 American Economic Association.

Zvi Griliches. R&D and productivity: Measurement issues and econometric results. *Science*, 237(4810):31–35, 1987.

Zvi Griliches. Patent statistics as economic indicators: A survey. *Journal of Economics Literature*, 28:1661–1707, 1990.

Bronwyn H. Hall, Adam B. Jaffe, and Manuel Trajtenberg. The NBER patent citation data file: Lessons, insights and methodological tools. Working paper, NBER, 2001.

Dietmar Harhoff, Francis Narin, F.M. Scherer, and Katrin Vopel. Citation frequency and the value of patented inventions. *The Review of Economics and Statistics*, 81(3):511–515, 1999.

Bracken Hendricks. Testimony to the house committee on resources oversight hearing on energy supply and the american consumer, executive director ,apollo alliance, February 12 2004.

John P. Holdren, William K. Reilly, John W. Rowe, and Philip R. Sharp. Ending the energy stalemate: A bipartisan strategy to meet americas energy challenges. Report, The National Commission on Energy Policy, December 2004.

Mark Z. Jacobson and Gilbert M. Masters. Energy: Exploiting wind versus coal. *Science*, 293(5534):1438–, 2001.

Michael Jefferson. Energy technologies for the 21st century. Report, World Energy Council, August 2001.

Charles I. Jones and John C. Williams. Measuring the social return to r&d. *The Quarterly Journal of Economics*, pages 1119–1135, 1998.

Daniel M. Kammen. The future of university nuclear science and engineering programs. In *U.S. House of Representatives Science Committee, sub-committee on Energy*, Washington, D.C., 2003.

Donald Kennedy. Climate change and climate science. *Science*, 304(5677):1565, 2004.

S. Kortum and J. Lerner. Does venture capital spur innovation? *Rand Journal of Economics*, 31:674–692, 2000.

Thomas Kuhn. Annual report of the u.s. shareholder-owned electric utility industry. Annual report, Edison Electric Institute, 2004.

Edwin Mansfield. Contribution of R&D to economic growth in the united states. *Science*, 175:477–486, 1972.

John H. Marburger. Science for the 21st century. Technical report, U.S. Office of Science and Technology Policy, July 2004.

Robert M. Margolis and Daniel M. Kammen. Underinvestment: The energy R&D challenge. *Science*, 285:690–692, 1999a.

Robert M. Margolis and Daniel M. Kammen. Evidence of under-investment in energy R&D in the united states and the impact of federal policy. *Energy Policy*, 27:575–584, 1999b.

Robert M. May. The scientific wealth of nations. *Science*, 275(5301):793, 1997.

Paul D. Maycock. PV news. Report, PV Energy Systems, 2005.

Ronald L. Meeks. Federal R&D funding by budget function: Fiscal years 2003-05. Report NSF 05-303, National Science Foundation, Division of Science Resources Statistics, 2004.

MIT. R&D scorecard 2002. *Technology Review*, 105(10):59, 2002.

M. Granger Morgan and Susan F. Tierney. Research support for the power industry. *Issues in Science and Technology*, 1998.

David C. Mowery. The changing structure of the U.S. national innovation system: Implications for international conflict and cooperation in R&D policy. *Research Policy*, 27:639–654, 1998a.

David C. Mowery. Collaborative R&D: How effective is it? *Issues in Science and Technology*, 15(1):37–44, 1998b.

Nebojsa Nakicenovic, Joseph Alcamo, Gerald Davis, Bert de Vries, Joergen Fenhann, and Stuart Gaffin. *Special Report on Emissions Scenarios, A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK, 2000.

PCAST. Report to the president on federal energy research and development for the challenges of the twenty-first century. Technical report, Office of the President, 1997.

PriceWaterhouseCoopers. Money tree survey. Report, PriceWaterhouseCoopers International Limited, 2001.

Rodrigo Prudencio. Nth power 2003 energy venture capital study. Technical report, Nth Power LLC, 2005.

Robert N. Schock, William Fulkerson, Merwin L. Brown, Robert L. San Martin, David L. Greene, and Jae Edmonds. How much is energy research and development worth as insurance? *Annual Review of Energy and Environment*, 24: 487–512, 1999.

Robert M. Solow. *Growth Theory: an Exposition*. Oxford University Press, Oxford, 2nd edition, 2000.

Donald E. Stokes. *Pasteur's quadrant: basic science and technological innovation*. Brookings Institution Press, Washington, D.C., 1997.

T. M. L. Wigley, R. Richels, and J. A. Edmonds. Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations. *Nature*, 379:240 – 243, 1996.

Raymond M. Wolfe. Research and development in industry. Report, National Science Foundation, Division of Science Resources Statistics, 2004a.

Raymond M. Wolfe. Personal communication: 'update on industrial R&D data', August 6 2004b.