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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 macroeconomic concerns. We 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 research and development (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. We 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.

Keywords: Energy R&D; Innovation; Patents

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 being 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, and 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 $100 billion 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; Kammen and Nemet, 2005), some on the scale of the Apollo Project of the 1960s (Hendricks, 2004). These recommendations

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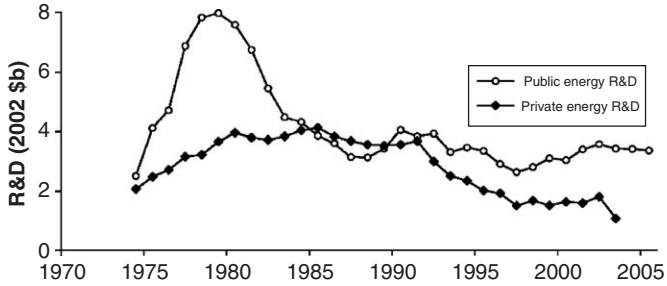

Fig. 1. Energy R&D investment by public and private sectors. The percentage of total R&D in the U.S. invested in energy technology has fallen from 10 to 2%. These time series are derived from federal budgets and from surveys of companies conducted by the National Science Foundation.

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,b). The scale of the energy economy, and the diversity of potentially critical low-carbon technologies to address climate change 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% from 2004 (AAAS, 2004a). The American Association for the Advancement of Science projects a decline in federal energy R&D of 18% by 2009 (AAAS, 2004b). 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% 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 declining 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 (Fig. 1) (Jefferson, 2001; Meeks, 2004; Wolfe, 2004). 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.

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, 1999a,b), 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 (Fig. 2). Moreover, the decline in investment in energy has occurred while overall U.S. R&D has grown by 6% per year, and federal R&D investments in health and defence have grown by 10–15% per year, respectively (Fig. 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 (Fig. 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 nation's 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

[1] See the "valley of death" discussion in PCAST (1997). Report to the President on Federal Energy Research and Development for the Challenges of the Twenty-First Century. Washington, Office of the President, Section 7–15.

[2] http://ist-socrates.berkeley.edu/~gnemet/RandD2006.html.

[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.

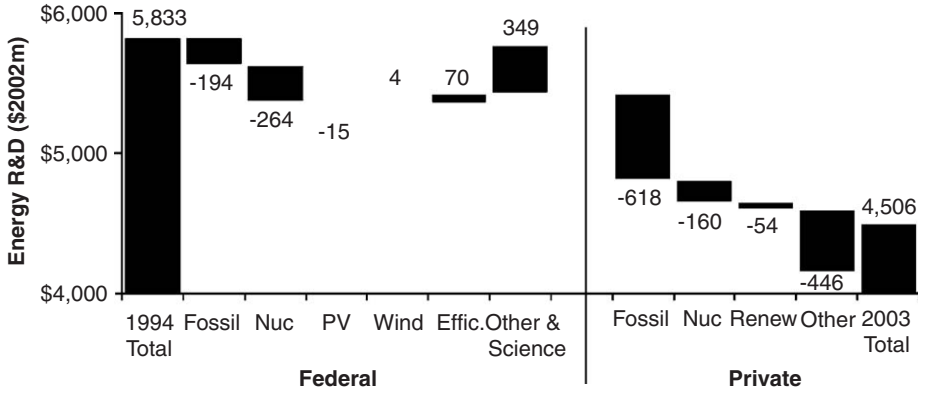

Fig. 2. Changes in energy R&D investment by sector and technology 1994–2003. The total change in R&D investment between 1994 and 2003 is disaggregated according to the contribution of each technology category and each sector. For example, of the $1327 million reduction in total energy R&D investment from 1994 to 2003, $618 million was due to the decline in fossil fuel funding by the private sector.

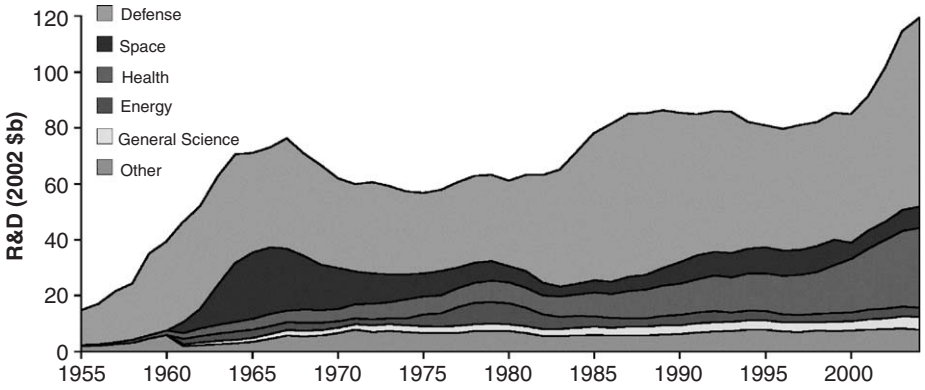

Fig. 3. Federal R&D 1955–2004. Annual level of R&D funding by budget function.

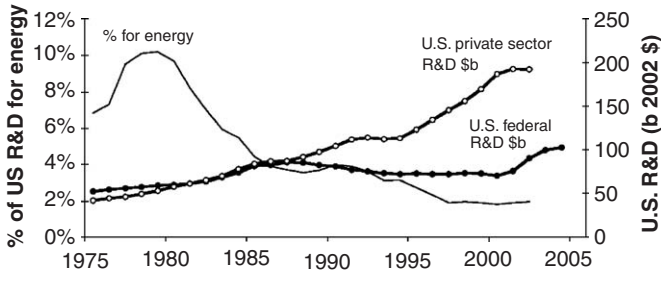

Fig. 4. Total U.S. R&D and percentage devoted to energy. Lines with circles indicate R&D investment levels in the U.S for all sectors. White circles show investment by companies and black circles federal government investment. Solid line indicates energy R&D spending as a percentage of total U.S. R&D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

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. First, the market for fossil fuel electricity generation has been growing by 2–3% per year and yet R&D has declined by half in the past 10 years, from $1.5 to $0.7 billion. 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 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. The lack of "demand pull" incentives 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, in which new capacity has been growing by 20–35% 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 renewable technologies.

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 $1 billion in 2000, and despite their subsequent cyclical decline to $520 million in 2004, are still of the same scale as private R&D by large companies (Fig. 5) (Prudencio, 2005). Recent announcements, such as California's plan to devote up to $450 million of its public pension fund investments to environmental technology companies and Pacific Gas and Electric's $30 million California Clean Energy Fund for funding new ventures suggest that a new investment cycle may be starting (Angelides, 2004). The emergence of this new funding mechanism is especially important because studies have found that in general, venture capital investment is 3–4 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 5000 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 (Fig. 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 four 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 $173 billion. Today, total private sector energy R&D is less than the R&D budgets of individual biotech companies such as Amgen and Genentech.

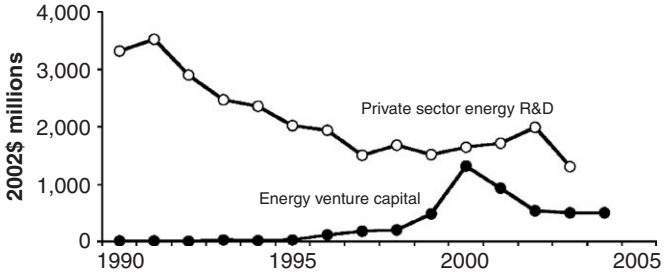

Fig. 5. U.S. Venture capital investments in energy and private sector energy R&D. Funding by companies (>500 employees) is compared to investment in emerging companies by venture capital firms.

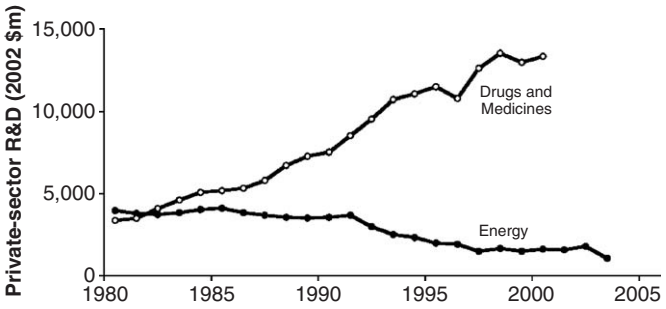

Fig. 6. Private-sector R&D investment: energy vs. drugs and medicines. R&D investment by companies in the energy sector is compared to investment by those in the drugs and medicines sector.

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 underperformance in the energy economy. In this section, we present results of three methods developed to assess patenting activity, which in earlier work has found to provide 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 public R&D and patenting across a variety of energy technologies (Fig. 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

[4]Patents data were downloaded from: USPTO (2004). U.S. Patent Bibliographic Database, www.uspto.gov/patft/. Alexandria, VA.

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

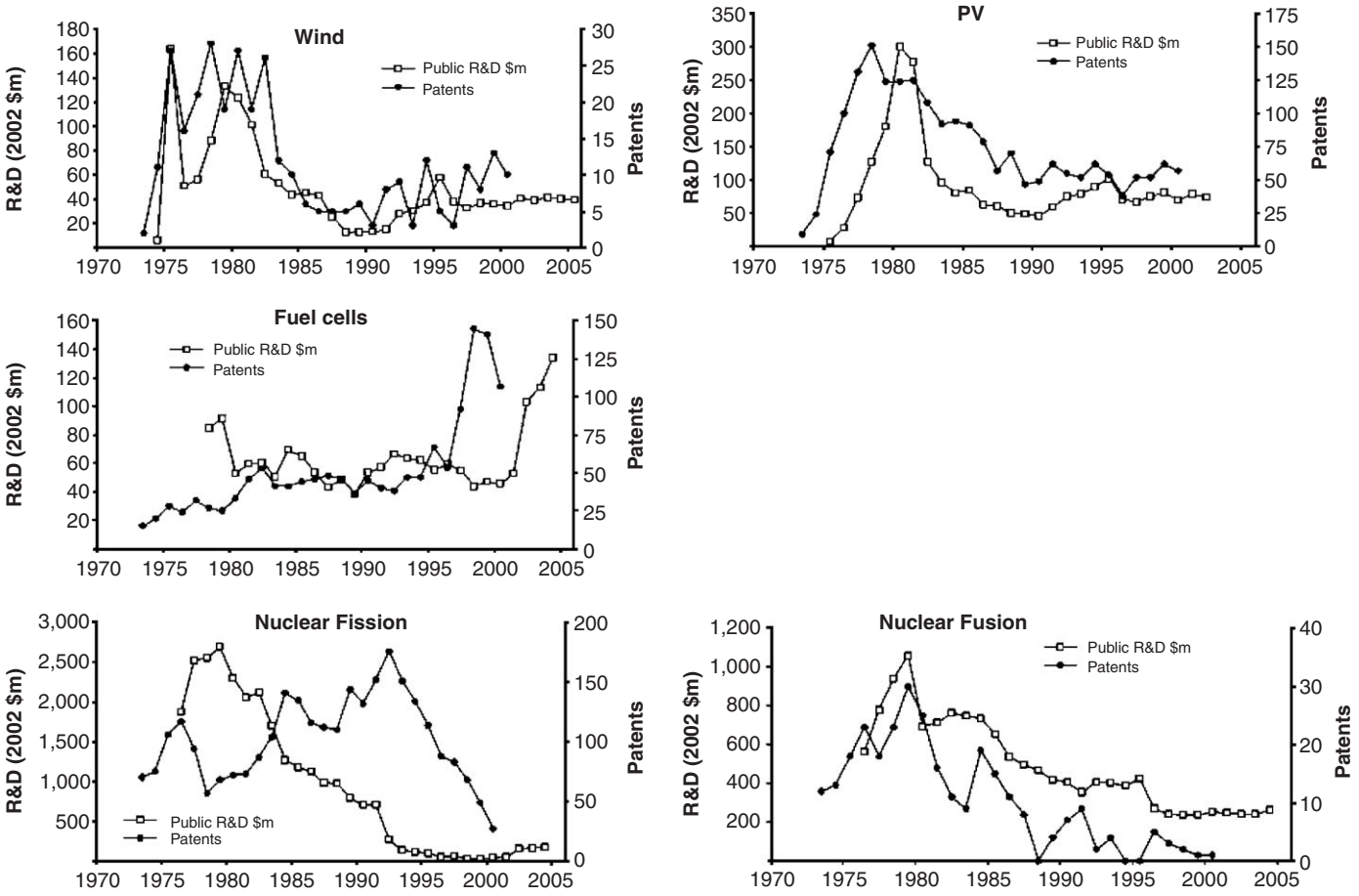

Fig. 7. Patenting and federal R&D. Patenting is strongly correlated with federal R&D. To provide comparisons with U.S. R&D funding, foreign patents are excluded. The data include granted patents in the U.S. patent system filed by U.S. inventors only. Patents are dated by their year of application to remove the effects of the lag between application and approval. This lag averages 2 years.

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.

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 this 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 randomly—they cluster in specific periods of productive innovation (Fig. 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 between the U.S. federal energy

[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.

[7]Analysis based on the citation weighting methodology of Dahlin et al. (2004). Today's Edisons or weekend hobbyists: technical merit and success of inventions by independent inventors. Research Policy 33, 1167–1183.

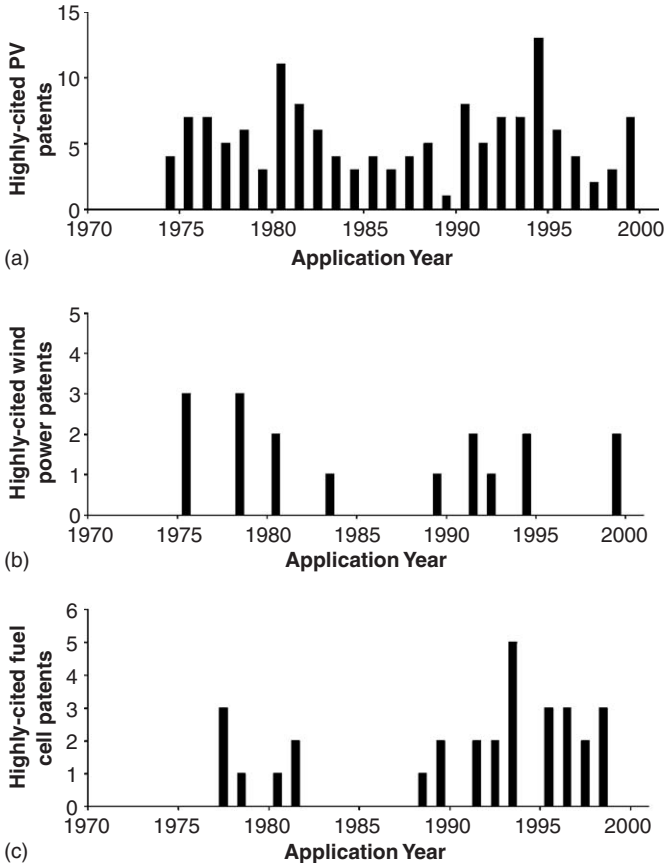

Fig. 8. Highly cited patents. For each patent the number of times it is cited by subsequent patents is calculated. "High-value" patents are those that received twice as many citations as the average patent in that technology category. Between 5 and 10% of the patents examined qualified as "high-value".

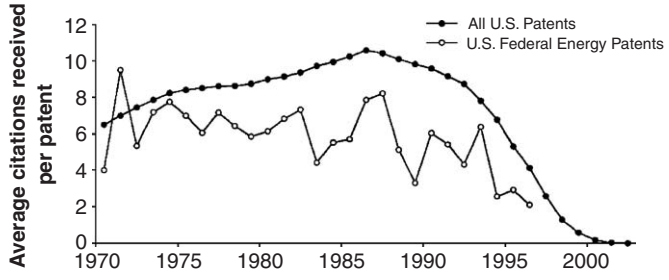

Fig. 9. Average patent citations received per patent granted. The *y*-axis indicates the average number of times a patent was cited by subsequent patents. The average of all patents filed during the year is shown on the *x*-axis. Recent patents, those issued within the past 5 years, were omitted because 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.

patent portfolio and all other U.S. patents is striking, with energy patents earning on average only 68% as many citations as the overall U.S. average from 1970 to 1997 (Fig. 9). This lack of development of government-

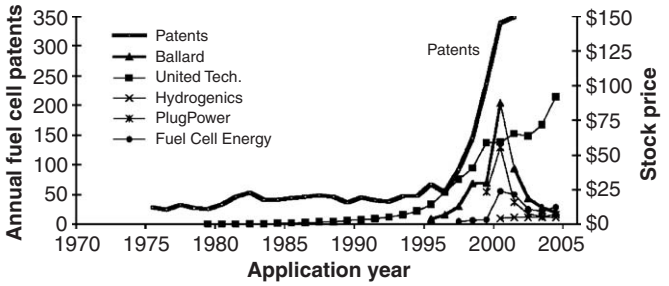

Fig. 10. Fuel cell patenting and stock prices. The relationship between fuel cell company stock prices and patenting is stronger than that between patenting and public R&D. The five firms shown account for 24% of patents from 1999 to 2004. Two hundred and eighty-eight firms received fuel cell patents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

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 (Fig. 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% 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, 1998a,b). 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 draw 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—while both the PCAST study of 1997 and the 2004 NCEP report 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 4 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 A1 T ("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–$27 billion, 6–9 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 5 times the current level and one for 10 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 five to ten-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 used 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 calculated 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 10× expanded energy investment scenario is within the range of the previous programs in all but one measure, where it exceeds by 10%. A 5× energy scenario is in the lower half of the range for each measure. Fig. 11 shows the scenarios (as circles) plotted against the range of previous programs. While expanding energy R&D to 5 or 10 times today's level would be a significant initiative, the fiscal magnitude of such a program is well within the range of previous programs, each of which have produced demonstrable economic benefits beyond the direct program objectives.

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 1975–1987 when private sector R&D averaged 1.1%, peaking at 1.4% in 1978. Overall R&D in the U.S. 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, 2004). 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

Table 1
Comparison of energy R&D scenarios and major federal government R&D initiatives (in constant 2002 dollars)

Program	Sector	Years	Peak year ($ billions)		Program duration ($ billions)		
			Spending	Increase	Spending	Extra spending	Factor increase
Manhattan Project	Defence	1940–1945	10.0	10.0	25.0	25.0	n/a
Apollo Program	Space	1963–1972	23.8	19.8	184.6	127.4	3.2
Project Independence	Energy	1975–1982	7.8	5.3	49.9	25.6	2.1
Reagan defence	Defence	1981–1989	58.4	27.6	445.1	100.3	1.3
Doubling NIH	Health	1999–2004	28.4	13.3	138.3	32.6	1.3
War on Terror	Defence	2002–2004	67.7	19.5	187.1	29.6	1.2
5× energy scenario	*Energy*	*2005–2015*	*17.1*	*13.7*	*96.8*	*47.9*	*2.0*
10× energy scenario	*Energy*	*2005–2015*	*34.0*	*30.6*	*154.3*	*105.4*	*3.2*

"Major R&D initiatives" in this study are federal programs in which annual spending either doubled or increased by more than $10 billion during the program lifetime. For each of these eight programs we calculate a "baseline" level of spending based on the 50-year historical growth rate of U.S. R&D, 4.3% per year. The difference between the actual spending and the baseline during the program we call *extra* program spending.

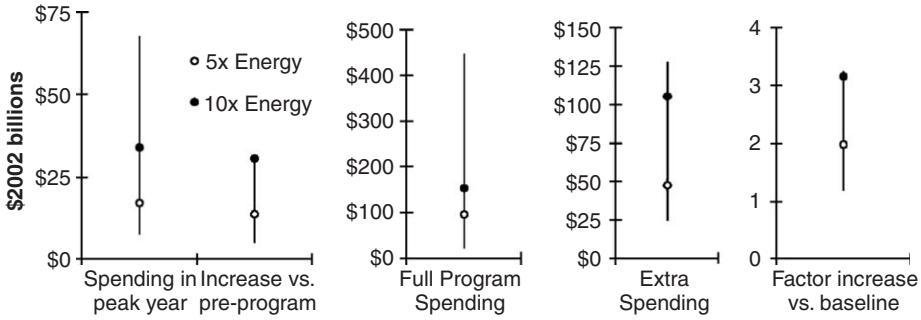

Fig. 11. Energy R&D scenarios plotted against the range of previous programs. For each of the five measures, the vertical line represents the range of values exhibited by the previous large federal R&D programs. The white circle indicates the value for a 5 × energy R&D scenario and the black dot for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

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 for this contention is weak or nonexistent. 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 macroeffects 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.[9] 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.[10] We found a similar result in a model explaining *private R&D*.[11] 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 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.[12]

[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.

[9]Although economic analyses of the value of research have found that costs of policies are highly sensitive to the presence of R&D crowding-out effects, the actual extent of crowding remains subject to widely varying assumptions. See Goulder and Mathai (2000). Optimal CO_2 Abatement in the presence of induced technological change. Journal of Environmental Economics and Management 38, 1–38, and Popp (2004). ENTICE-BR: The Effects of Backstop Technology R&D on Climate Policy Models. Cambridge, MA, NBER.

[10]Regression model for other Federal R&D:

$$\log(\text{Other-fed-RD}) = \underset{(0.06)}{3.35} + \underset{(0.01)}{0.03}\text{*}\log(\text{program-RD}) + \underset{(0.03)}{0.43}\text{*}\log(\text{GDP}) + e$$

$n = 31$, $r^2 = 0.87$, *coefficient is significant at 95% level.

[11]Regression model for Private R&D:

$$\text{Private-RD} = \underset{(5.22)}{-87.2} + \underset{(2.31)}{7.40}\text{*}(\text{program-dummy}) + \underset{(0.60)}{25.8}\text{*}\text{GDP} + e$$

$n = 28$, $r^2 = 0.99$, *coefficient is significant at 95% level.

[12]In the 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.

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 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 that 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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