HOW MUCH IS ENERGY RESEARCH & DEVELOPMENT WORTH AS INSURANCE?

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■   **Abstract**   In this paper, we estimate the value of energy technology research and development (R&D) as an insurance investment to reduce four risks to the United States. These four risks are (*a*) the costs of climate stabilization, (*b*) oil price shocks and cartel pricing, (*c*) urban air pollution, and (*d*) other energy disruptions. The total value is estimated conservatively to be >$12 billion/year. However, only about half of this total may be warranted because some R&D is applicable to more than one risk. Nevertheless, the total Department of Energy investment in energy technology R&D [∼$1.5 billion/year in fiscal year 1999 (FY99)] seems easily justified by its insurance value alone. In fact, a larger investment might be justified, particularly in the areas related to climate change, oil price shock, and urban air pollution. This conclusion appears robust even if the private sector is assumed to be investing a comparable amount relevant to these risks. No additional benefit is credited for the value to the economy and to the competitiveness of the U.S. from better energy technologies that may result from the R&D; only the insurance value for reducing the potential cost of these four risks to society was estimated.

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INTRODUCTION

Over the decade from 1985 to 1994, the total U.S. investment in energy research and development (R&D) (both public and private) decreased from ~$7 billion/year to $5 billion/year (in 1995 constant dollars) (1, 2). The same trend was observed in the public sectors for other Organization for Economic Cooperation and Development (OECD) countries, where the combined investments declined by $3 billion/year or 25% in real terms over the decade. Only Japan and Switzerland increased spending (3).

The United States spends ~$500 billion/year for fuels and electricity. Thus, ~1% of energy expenditures (i.e. $5 billion/year) is spent on R&D. The United States invests ~$175 billion/year on all R&D, of which ~$75 billion is federal, with more than half of that allocated for defense. Thus, only ~3% of total R&D investments is spent on energy, although energy contributes ~8% to the gross domestic product.

So what? Why should anyone care about R&D funding? After all, there is no energy crisis (and there hasn't been one since the Gulf War, when a very brief oil price excursion occurred after the invasion of Kuwait by Iraq in 1990); most environmental insults from energy production and use are being reduced, and energy prices are stable and generally low. Crude oil prices are lower than at any time since 1973, and gasoline prices in the United States are at an all-time low. Arguably, this improved situation is the result, at least partially, of the development and deployment over the past two decades of better energy technologies, for example, for oil and natural gas production, exploration, conversion, and end use.

We should care about the level of R&D funding because important risks remain, and energy is too important to ignore. Jack Gibbons, former Assistant to the President for Science and Technology, recently wrote to the President transmitting the report of the Panel on Energy R&D of the President's Committee of Advisors on Science and Technology (PCAST) (4):

> PCAST endorses the Report's findings that this country's economic
> prosperity, environmental quality, national security, and world leadership in

science and technology all require improving our energy technologies, and that an enhanced national R&D effort is needed to provide these improvements.

But how much should we be willing to pay for this R&D?

In the following sections, we describe four continuing energy-related risks and discuss the potential for energy R&D to reduce the cost to society, should the risks prove real. The value of this insurance is estimated and compared with the current Department of Energy (DOE) energy technology R&D investments.

Successful R&D is a necessary means to reduce potential costs from risks, but it may not be sufficient for full management of these risks. Policies to stimulate additional R&D by the private sector or to encourage the early adoption of resulting better technologies may also be needed as part of any insurance strategy (4).

ENERGY RISKS

Four risks are considered: (*a*) climate change, (*b*) oil price shocks and the Organization of Petroleum Exporting Countries (OPEC) impact on oil prices, (*c*) urban air pollution, and (*d*) energy system disruptions other than oil price shocks. The consequences of these risks are borne by society and as such are the concern of government. To the extent that R&D can reduce the risks, government should provide the necessary encouragement and/or sponsorship. The private sector alone is unlikely to carry out or sponsor all the necessary R&D because (*a*) there is insufficient return on its investment or (*b*) the benefits accrue to society in general rather than to any industry segment or single firm. On the other hand, the private sector must be a partner with government if technology derived from R&D is to be effectively commercialized and adopted.

In this analysis, various energy technology R&D activities were observed to be almost always relevant to multiple risks. For example, work on automobile power systems that gradually transform them to much more efficient hydrogen fuel cells will have a profound impact on greenhouse gas emissions as well as on urban air pollution and oil security.

Climate Change

Potentially adverse climate change caused by emissions of greenhouse gases, particularly CO_2, which is a byproduct of the combustion of fossil fuels, is a global long-term risk. Reducing this risk will require decades, if not a century, of effort. The environmental impact from changes in the atmospheric concentrations of these gases is uncertain, as is the cost of mitigation of adverse climate change (5). Nevertheless, should it prove necessary, mitigating climate change will have a profound effect on the energy systems of the world, which, at present, are 75% dependent on fossil fuels. The use of fossil fuels must be curtailed and/or a way must be found to use them without adding CO_2 to the atmosphere. Wigley

et al (6) estimated the cost of optimally timed mitigation strategies for stabilizing the atmosphere at various levels of CO_2 concentrations. Their analysis takes into account the evolution of energy technologies, the turnover of capital stock, and the growth of world economies and population. They calculated that the discounted present-value cost to the global economy of stabilizing CO_2 concentration in the atmosphere at 550 ppm by volume would be ~$1 trillion, discounted at 5% per year over the time period necessary to stabilize the concentration (centuries). The cost increases as the stabilization concentration decreases and vice versa.

Subsequently, Edmonds et al (7) estimated that this cost of stabilizing CO_2 concentration at 550 ppm by volume could be reduced to nearly zero if certain advanced technologies were developed and deployed beginning in the decade from 2015–2025. These include nonfossil, electric generation technologies producing electricity for <$0.04/kWh, biomass fuels with a cost of $1.5–2.4/GJ, and high-efficiency, fuel cell vehicles competitive in cost and performance with the best internal-combustion-engine vehicles. Obviously, climate change is one risk factor for which energy technology R&D can make an enormous difference. Given the uncertainties about the risks, doing the R&D would seem to provide very low-cost, effective, and prudent insurance. Note that, in this calculation by Edmonds et al, no attempt is made to estimate what might be saved by stabilizing the atmospheric concentration of CO_2 at 550 ppm by volume, in terms of avoided "bad effects" from exceeding that level. Calculating bad effects is very uncertain, so the emphasis was on the potential for advanced technology to reduce mitigation costs instead.

Oil Price Shock and Cartel Impact on Prices

Monopolistic pricing of oil by the OPEC cartel, whose core members are Saudi Arabia, Iran, Venezuela, the United Arab Emirates, Kuwait, Iraq, and Libya, has been estimated to have cost the U.S. economy ~$4 trillion (1990 dollars) over the period 1973–1991 (8). A substantial fraction of this loss occurred as a result of oil price shocks in 1973–1974 and 1979–1980, which were caused by the Arab oil embargo of 1973–1974 and the Iran-Iraq war of 1979–1981, respectively. The costs to the U.S. economy included transfer of wealth to OPEC countries, decreases in the rate of growth of gross domestic product, and macro-economic adjustment losses that result because wages and prices are not able to adjust rapidly enough to the new oil price regime to permit the economy to operate at full employment (8).

Could such shocks happen again? Since 1986, OPEC—especially the Middle East core members—has been regaining world market share. This is the key condition that returns power for manipulating prices to a von Stackelberg-type cartel (9, 10). It is the condition that concerns the community who worry about energy security (11) and, because of the large fraction of world low-cost oil reserves and estimated resources remaining in the Middle East, will make oil price shocks

more likely with time. Greene et al (9) make assumptions about the behavior of OPEC and then model the response of the United States and worldwide oil markets to a 2-year curtailment of the oil supply of the same magnitude that occurred in 1973–1974 or 1979–1980. If this were to occur in the middle of the next decade when core OPEC market share has risen to ∼40%, the loss to the U.S. economy is estimated to be ∼$400 billion, and OPEC's gain ∼$500 billion (9, 12). The Strategic Petroleum Reserve is not effective against such a large curtailment. What would be effective are those technologies that reduce the cost of energy efficiency improvements, create more attractive substitute fuels, or make it less costly for non-OPEC states to find and produce oil. Examples of such technologies are those being developed by the Partnership for a New Generation of Vehicles (PNGV), an alliance between the Big-Three United States automotive manufacturers and the government. This alliance aims to bring to market a cost-effective, five-passenger car with 80-miles/gal (mpg) fuel efficiency that does not sacrifice performance or safety. It appears that the Big Three may have decided that much more efficient and cleaner power systems are essential for their competitive futures, a bit of a "sea change" (13).

The probability and timing of another oil price shock cannot be predicted. Some believe the probability is very small (14, 15). Nevertheless, the cost of such a shock could be very large, but even if such a shock does not occur, cartel pricing may still result in very high costs to the U.S. economy, perhaps as high as $700 billion from 1993 to 2010 (12). R&D for technologies to reduce these large costs can be inexpensive insurance, and these technological changes would also decrease the likelihood of a price shock. In fact, improvements in technologies of oil discovery and production over the past decade are likely a contributing factor to the current very low oil prices, but the suddenness of the price decline suggests that other factors are also important.

In December of 1998, crude oil prices fell to their lowest levels since before the first oil supply shock in 1973. With Arabian Light selling for $8/barrel (bbl) and West Texas Intermediate at $11/bbl, worries about oil supplies might justifiably seem passé (16). And although prices have rebounded somewhat in recent months, today's markets are awash in oil. Are current oil market conditions temporary or a permanent reprieve from worries about oil market disruptions?

Those who argue that the good times are temporary note that the fundamental distribution of oil reserves and resources in the world remains unchanged and that the majority of present production is coming from fields ≥20 years old. These analysts foresee a peak in world oil production in the coming decades, possibly as early as 2001, followed by a serious tightening of world oil supplies and a renaissance of OPEC market power (see 17–20). The current situation could be attributed to a combination of factors:

1. The Asian economic crisis
2. A sudden 1 million bbl/d increase in supply from Iraq between 1997 and 1998 (21)

3. OPEC members continuing to exceed their self-imposed production quotas
   (22)

4. Continued high production from non-OPEC countries outside of the
   United States, reflecting advances in the technologies of oil exploration
   and production (23)

Those who argue that abundant oil supplies are likely to be much longer lasting
cite the following:

1. Advances in the geosciences and in the technologies of exploration,
   development, and production

2. The still limited exploration of many frontier areas

3. The vast unconventional hydrocarbon resources like oil shale and tar sands
   that, with further advances in technology, could result in abundant liquid
   fuels for the next century (see 24).

Although we cannot resolve these different views here, two points are relevant
for the purposes of our analysis. (*a*) Even those who believe that oil supplies
will be abundant in the long run expect some sort of short-term disruptions. For
example, although the U.S. Energy Information Administration's *International
Energy Outlook 1998* anticipates that oil prices will rise gradually to $23/bbl in
2020, it still notes that short-term disruptions are likely. "In the future one can
expect volatile behavior to recur principally because of unforeseen political and
economic circumstances" (25). (*b*) The principal driving force enabling low oil
prices and abundant supplies in the future is always technology. Thus, in a sense,
these analyses anticipate the success of R&D aimed at discovery, production, and
conversion of liquid hydrocarbons. In the latter case, the argument is not over the
value of R&D, but rather who should do what part of it.

As for climate stabilization, other policies could also be effective, for example,
a tax on oil use or oil imports. If large enough, this would retard oil use and likely
would stimulate R&D or other strategies as well. The drawback is that it could
be very expensive to the economy, as high as $100 billion/year depending on how
the revenues are used (26).

Urban Air Pollution

Much of urban air pollution results from energy use in vehicles and industry and in
the production of electric power. The resulting increased medical costs and time
lost from jobs are not well quantified, but they are certainly >$10 billion/year,
which is an estimate for the Los Angeles Basin alone (27, 28). Estimates of air
pollution costs for the whole country from motor vehicle emissions range from
$20–300 billion/year. (See an excellent summary in 29.) Much is being done, and
air quality in most U.S. cities is improving. Cleaner and more cost-effective energy
technologies ensure continued improvement in air quality. R&D is the price of

these better technologies, and the payoff is reduced pollution at less cost. This risk is a bit different from the others. In this case, we know that air pollution causes damages, although we do not know exactly how to price the damages. Energy R&D can lead to technologies that can be used to reduce the damages at less cost. R&D is not insurance against the probability of an uncertain bad consequence. In this case, the bad consequence—air pollution—is actually occurring, and the R&D may reduce the cost of mitigation.

The principal policy for reducing urban air pollution is regulation, including marketable emission limits and ambient air standards. In California and several other states, the sale of zero-emission vehicles was mandated. No doubt these policies also act to stimulate R&D and innovation. These incentives complement government R&D programs.

Energy Disruptions

The energy infrastructure of the United States is remarkably resilient to disruptions. Disruptions do occur, however, and are generally related to natural phenomena such as weather. Disruptions can be expensive and even hazardous to human health and well being. Because of deregulation in the electric system, reliability could suffer, but there are many other potential causes, ranging from aging infrastructure to sabotage.

Remotely located infrastructures for pipes and wires have always provided tempting targets for physical assaults, but we have yet to experience a major act of sabotage in the United States that resulted in a substantial power outage. On the other hand, sabotage in South America, Africa, and Europe has been much more frequent and has caused outages of several weeks (30). Recent events in the United States have caused speculation that physical terrorism might be on the rise.

A growing dependence on communications and information management in energy delivery systems has added a new terrorist-related risk. "White collar" saboteurs wielding electronic and computer-based "weapons" pose an even greater threat of disruption than physical assaults on our energy delivery systems. Information has always been important to managing electric transmission systems, but less so for distribution. To give some perspective on this dependence, one utility reported having 20,000 personal computers, two mainframes, 460 local area networks, and a corporate database of 1.45 terabytes (31). But the volume of data, the speed with which it must be handled, and its importance to maintaining secure and stable systems have all been increasing in both electric transmission and distribution systems. Control systems are becoming increasingly reliant on electronic and computer-based devices and systems. Although these control systems are isolated from the general public, which makes access relatively difficult, they are probably not immune to attack. Some utilities plan to use the Internet for energy brokering, communicating with customers in "real-time" (32), and other forms of electronic

commerce; these innovations will likely increase the vulnerability to this form of energy disruption. Concern over just such energy disruptions in electric grids in particular and other U.S. infrastructures in general led to the formation of the President's Commission on Critical Infrastructure Protection, which was established by presidential order in July 1996. The Commission calls this new form of disruption cyber threats.

> Today, the right command sent over a network to a power-generating station's control computer could be just as effective as a backpack full of explosives, and the perpetrator would be harder to identify and apprehend. The rapid growth of a computer-literate population ensures that increasing millions of people possess the skills necessary to consider such an attack (33).

Simultaneous attacks on control systems throughout a regional grid could be made by electronic and physical terrorists. Unfortunately, grid operators are not armed with the same levels of sophistication in tools and experience to deal with electronic disruptions, compared with their preparedness for disruptions caused by weather, for example. Disruptions caused by electronic tampering, consequently, have the potential to dwarf the consequences from more conventional causes, like losing a major intertie because of grounding to a tree.

Perhaps the most pervasive, yet subtle factors in the reliability of energy delivery systems are the impending pressures of competition and new regulatory requirements. Although electric loads have increased at ~2% annually over the last decade, very little capacity has been added to the transmission systems during this time. This construction hiatus has been attributed in part to siting difficulties, but at costs approaching $1 million per mile, capital has also been a factor (32). Consequently, desires to increase asset use and cut costs can cause delivery systems to be operated much closer to their design limits or in ways for which systems were not designed, and they can thus raise the exposure to disruptions. This exposure is compounded because, with current technology, one rarely knows where the limit truly is.

All of these modes of energy system disruption have the capacity to increase negative consequences in the future. As grids, particularly electric grids, become larger and more tightly integrated, a relatively small event can cause major disruptions thousands of miles away almost instantaneously. Fortunately, there are a number of potential solutions for mitigating many reliability problems of energy delivery systems. Some of these involve the development of better technologies.

HOW MUCH IS R&D INSURANCE WORTH?

A rough estimate can be made of how much society should be willing to pay in the form of R&D as insurance to reduce the potential costs of managing the four

risks.[1] There is much uncertainty in the numbers. Conservatism was used in the sense that the probabilities of losses estimated are on the low side of the range of uncertainty, as are the probabilities of R&D success. The choices and calculations are exposed. Finally, the potential insurance value of R&D investments is compared with the actual fiscal year 1999 (FY99) DOE budget applicable to each risk area.

For each risk, we calculate the insurance "premium" value of R&D, V, as follows: $V_{R\&D} = CpE$, in which C is the net present discounted cost of the loss, p is the probability of suffering the loss, and E is the effectiveness of R&D to reduce the cost should the loss actually be incurred. The effectiveness, E, is equal to the sum over all relevant technologies of the product of the probability of R&D success for any technology, over some number of years of R&D investment, times the potential of that technology for reducing the loss. This variable is admittedly subjective, and its value derives from our judgment in predicting R&D success. Table 1 summarizes the estimated values in this equation for each of the four risks as discussed below.

Climate Change

It is assumed, after Edmonds et al (7), that better technologies can reduce the cost to world societies of stabilizing the climate by limiting CO_2 concentration to various levels as shown in Table 2. Rather than focusing on any one concentration, probabilities of needing to stabilize at various concentrations are assumed. To be on the conservative side, the chance that no stabilization action at all will be required was put at 35%; then, the remaining 65% was divided up among the values ≤450, 550, 650, and 750 ppm by volume. Then the cost of stabilization was calculated for two mitigation scenarios, the one proposed by Wigley et al (6) and the one proposed by Working Group 1 of the Intergovernmental Panel on Climate Change (34). Possible cost savings of better technologies were estimated using the models of Edmonds et al (7, 35) for each of these scenarios. Summing these

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[1]Calling this investment in R&D insurance seems a reasonable, but imperfect, analogy. In this case, an investment is being made to reduce the cost of a future uncertain risk. That is why one takes out insurance, as a hedge against the cost of an uncertain risk. On the other hand, when one pays an insurance premium, the policy is guaranteed to pay off if and when the uncertain event occurs, and this is not true for R&D investment. There is no guarantee the investment will succeed, and hence the need to moderate the "insurance value" by multiplying with the probability of success. Still, R&D may be the best hedge available to society against the risk, and its success rate will increase with increasing R&D expenditure. The term "loss prevention technology" might be a more exact term, but it is also less easily understood. For this reason, we use the term "insurance" in this paper.

The four risks discussed here are not a comprehensive set. They are important and represent situations in which market forces alone are unlikely to encourage adequate R&D. Other risks to society deriving from energy circumstances might also be reduced by appropriate R&D, such as eventual resource depletion or the loss of control of nuclear materials.

TABLE 1 The insurance value of energy R&D investments for various risks, using the equation $V_{R\&D} = CpE$

Risk factors	Climate change	Oil price shock	Urban air pollution	Energy disruptions
Potential cost to United States (C)	Varies with stabilization concentration[a]	$400 B plus the cost of paying cartel-inflated prices without a shock[b]	>$20 billion/year	$26 billion/year for electricity disruptions alone
Probability of incurring cost (p)	Varies[a]	0.5 (over next 15 years)	1.0[c]	1.0[c]
Effectiveness of R&D to reduce cost (E)	Varies[a]	0.1[d]	0.2 in 10 years[d]	0.1 × (10%–30%) = 1%–3% in 10 years[d]
Insurance premium value of R&D (V)	$3–7 billion/year	>$6 billion/year for 10 years[e]	>$2 billion/year[e]	$0.2–0.5 billion/year[e]
DOE's FY99 investment in R&D relevant to this risk[f]	$1.1 billion/year	$0.7 billion/year	$0.9 billion/year	$0.4 billion/year

[a] See Table 2.

[b] See Table 4.

[c] Occurring now.

[d] Conservative guess.

[e] Discounted at 5%.

[f] See Table 3.

cost savings over all four stabilization concentrations and both sets of scenarios (assuming both scenarios are equally likely) gives the potential value of R&D as $0.83 trillion current dollars. It was further assumed that the U.S. share of the R&D cost is equal to its fraction of current global greenhouse gas emissions (∼25%). The probability of R&D success is assumed to vary between 0.1 for 450 ppm and unity for ≥650 ppm (Table 2). This yielded a present value of the R&D investment of $0.1–0.14 trillion by using a discount rate of 5%. The corresponding annualized R&D expenditure range thus justified is from 0.05 × $100 billion to 0.05 × $140 billion, or $5–7 billion/year. If only the Wigley et al (6) strategies are considered, the values are $0.053–0.072 trillion and $3–4 billion/year, respectively.

In these estimates, the crucial number is, of course, the assumed probability that the CO_2 concentration must be stabilized at these various levels. The numbers assumed can be rationalized but not justified. Clearly, the move by the United

TABLE 2   Estimated value of energy technology R&D for climate stabilization[a]

	Target atmospheric stabilization concentrations (ppm by volume)				
	450	**550**	**650**	**750**	**None**
1. Probability of needing to stabilize at each level	0.05	0.25	0.2	0.15	0.35
2. Cost to stabilize (WRE)	3.7	0.9	0.3	0.2	
3. Cost with R&D success	0.4	~0	~0	~0	
4. Potential savings with R&D = $1 \cdot (2 - 3)$[b]	0.17	0.23	0.06	0.03	
5. Cost to stabilize (WG1)	4.5	2.4	1.3	0.5	
6. Cost with R&D success	0.4	~0	~0	~0	
7. Potential savings with R&D = $1 \cdot (5 - 6)$	0.21	0.6	0.26	0.07	
8. Average cost savings assuming WRE and WG1 are equally likely = $(4 + 7)/2$	0.19	0.41	0.16	0.05	
9. U.S. share (~25%) = $8 \cdot 0.25$	0.046	0.1	0.04	0.013	
10. Assumed probability of R&D success	0.1	0.5–0.8	1	1	
11. R&D value = $9 \cdot 10$	0.0046	0.05–0.08	0.04	0.013	
Sum of R&D values over all stabilization levels			0.11–0.14		
Annualized R&D expenditures justified			0.0055–0.007		
Annualized R&D expenditures justified for WRE only			0.0027–0.0036		

[a]Calculations of the stabilization costs in trillions of 1999 dollars were made using the world MiniCAM 2.0 model (35). All costs were discounted at 5%. The value of R&D was calculated for two mitigation scenarios: Wigley et al (6) (WRE) and Intergovernmental Panel on Climate Change (34) (WG1).

[b]Value of row 1 times the difference between the values of row 2 and row 3; e.g. for 450 ppm row 4 is equal to 0.05 times (3.7–0.4) or $0.17 trillion.

States and other Organization for Economic Cooperation and Development countries to set binding targets in Kyoto for emissions of greenhouse gases indicates the seriousness with which many view the risk, but no agreement was reached about what the stabilization concentration should be. The lower the stabilization concentration, the more expensive it will be to meet the target, and the more valuable will be the development of advanced technologies, but the time for development would be shorter. For example, if stabilization at 450 ppm by volume were required, advanced technology might save 3.5-fold the 550-ppm-by-volume case, provided that this advanced technology was available 10 years earlier (7). If stabilization at 650 ppm by volume were required, advanced technology might save only one-third to one-half as much as for 550 ppm, and the time for developing the technology would be stretched another decade or more.

Because of this time factor, the probability of R&D success was judged to increase with the stabilization concentrations as shown in Table 2. We believe there is a high probability of technological success in the next 15–20 years, assuming that adequate investments continue to be made. That is, we think there is a good chance carbon-free energy sources can be developed that generate electricity at less than $0.04/kWh, biomass feedstocks of $1.5–2.5/GJ can be produced, and fuel-cell-powered vehicles competitive with internal-combustion vehicles can be developed in this time period. However, a determined and continuing R&D effort will be required to achieve these goals.

On this basis, the overall insurance value of this R&D is between $3 billion and $7 billion/year to the United States. It should be noted, however, that the Wigley et al (6) and Intergovernmental Panel on Climate Change reference cases already assume a substantial and continuing improvement in technology. If current state-of-the-art technology had to be solely relied on, the cost of stabilization would have been approximately threefold higher. This autonomous improvement implies a considerable R&D benefit indicating that the insurance value of R&D is at least threefold greater, or $9–21 billion/year. To be conservative, we stay with the $3–7 billion/year value.

The FY99 DOE energy technology R&D budget was analyzed for relevance to this climate change risk. The results of our analysis (Table 3) indicate that, in FY99, the DOE was spending ∼$1.1 billion in mitigation-relevant research; an expenditure one-third to one-seventh as large as can be justified from the above argument. However, it should be noted that this investment often leverages a substantial matching contribution from the private sector. So, although the government investment is much less than is justified by the insurance value, the relevant total national effort is larger.

Many R&D opportunities that may lead to reducing greenhouse gas emissions at lower costs are elaborated in three reports: PCAST (4), *Scenarios of U.S. Carbon Reductions* (36), and *Technology Opportunities to Reduce Greenhouse Gas Emissions* (37).

One example of these opportunities was given recently by Williams (38), who suggested that fossil fuels be used in a greenhouse-gas constrained economy to

TABLE 3 Department of Energy energy technology R&D investments for FY99 as allocated to the four risks of climate change, oil price shocks and oil cartel pricing, urban air pollution, and energy disruptions[a]

Energy technology R&D area[b]	FY99 budget	Climate change		Oil price shock		Urban air pollution		Energy disruptions	
		Relevance	Relevant budget	Relevance	Relevant budget	Relevance	Relevant budget	Relevance	Relevant budget
Fossil energy	384	Varies	192	Varies	197	Varies	236	Varies	89
Coal	123	Varies	67	Varies	62	Varies	111	Varies	22
Advanced clean fuels	15	L	3	M-H	11	L	3		
Advanced clean/efficient power	88	M	44	L-M	31	H	88	L	18
Advanced R&D	20	H	20	H	20	H	20	L	4
Petroleum	49	L	10	H	49	L	10	L	10
Gas	115	H	115	Varies	86	H	115	M	57
Natural gas research	71	H	71	H	71	H	71	M	35
Fuel cells (high temperature)	44	H	44	L-M	15	H	44	M	22
Miscellaneous (environmental restoration and partnerships)	25								
Plant and equipment	3								
Program development and management	69								
Energy efficiency	502	Varies	464	Varies	304	Varies	416	Varies	171
Transportation	202	H	202	H	202	H	202	L	40

(continued)

TABLE 3 (*continued*)

Energy technology R&D area[b]	FY99 budget	Climate change		Oil price shock		Urban air pollution		Energy disruptions	
		Relevance	Relevant budget	Relevance	Relevant budget	Relevance	Relevant budget	Relevance	Relevant budget
Industry	166	H	166	M	83	H	166	M	83
Buildings	96	H	96	L	19	M	48	M	48
Policy and management	38								
Renewables	384	Varies	342	Varies	171	Varies	266	Varies	157
Photovoltaics	75	H	75	L	15	H	75	M	37
Biofuels	100	H	100	H	100	M	50	L	20
Solar buildings	8	H	8	L	2	H	8	M	4
Solar thermal energy	17	H	17	L	3	H	17	L	3
Wind	35	H	35	L	7	H	35	M	17
Renewable incentive program	4	H	4	L	1	H	4	M	2
Resource assessment	5	H	5	L	1	H	5		
International and tech transfer	6	H	6	M	3	H	6		
Geothermal	29	H	29	L	5	M	15	M	15
Hydrogen	25	H	25	H	25	H	25	M	13
Hydropower	3	H	3	L	1	H	3	M	1
Electric energy systems and storage	40	M	20	L	8	L	8	H	40
Solar photoconversion	15	H	15	L	3	H	15	L	3

	Total								
Policy and management plus NREL	22								
Nuclear fission[c]	55	Varies	30	Varies	6	Varies	30	Varies	6
Nuclear energy research initiative	19	H	19	L	4	H	19	L	4
University research and test reactor support	11	H	11	L	2	H	11	L	2
Program direction and management	25								
Nuclear fusion	223	M	111						
Total energy technology R&D	1548		1139		678		948		421
Office of Science (not including fusion)	1395								
Basic energy science (BES)	800								
Computational and technology research (CTR)	158								
Biological and environmental research (BER)	437								
Total energy R&D, including BES, CTR, and BER	2943								

[a]R&D in a given area may be relevant to more than one risk, thus the sum budget amounts for the four risks add up to more than the FY99 budget totals.

[b]Not included under fission is any part of the $358 million for the Office of Civilian Radioactive Waste Management funded in part by a tax on utilities with nuclear power plants for the purpose of establishing a permanent repository for spent nuclear fuel. Also, no part of the $205 million budget for nonproliferation by the Office of Nonproliferation and National Security is included. Also, not included is $503 million being spent on inertial fusion research associated with nuclear weapons by DOE's defense programs. Some significant part of the budget for the Office of Science is applicable as basic research support for the energy technologies, but allocation to each risk area is unknown.

[c]H, High relevance (we assume the whole budget counts for that particular risk); M, medium relevance (we assume half the budget counts); L, low relevance (we assume 0.2 of the budget counts); blank space, the R&D counts zero.

provide hydrogen to power vehicles. The idea may be practical if fuel cells become the power source of preference for high-efficiency, high-performance, and low-emission vehicles and if these innovations create a demand for a hydrogen-fueled transportation sector. In a greenhouse-effect constrained society, fossil fuels may still be the least expensive way to produce hydrogen, even if the CO_2 produced in its manufacture must be sequestered (e.g. in depleted gas wells or deep saline aquifers). To examine this possibility, research on sequestering CO_2 is needed, and more work needs to be done on fuel cells and the thermochemical processes for producing hydrogen. Another important related option is the production of hydrogen from biomass, with and without sequestering. Work is needed on biomass and municipal solid-waste gasification (4).

A second area in which increased R&D might have significant promise is the nuclear fission option. More R&D might be directed at increasing proliferation resistance, at creating more nearly foolproof reactor safety, and at reducing the cost of nuclear power (39, 40).

A third area is R&D focused specifically on technologies attractive to developing nations. The choices these countries make will be crucial to stabilizing the climate. An example of an important R&D target is the development of a small-scale biomass electric generator for rural electrification that is also cost effective, efficient, clean, and user friendly and that can cogenerate electric power and process heat.

Oil Price Shock (Oil Market Distortions)

Although the chances of another oil price shock may seem remote today, the probability of a disruption will increase in the future as OPEC regains its former share of the world oil market. The cost to the U.S. economy of a single 2-year shock occurring in the next decade has been estimated at >$400 billion in present value (12). By the end of the next decade, the core OPEC market share is projected to be at pre-1973–1974 oil embargo levels of ∼40% (12).

What might be the probability of such an oil price shock? We don't know, but the world has experienced three such shocks over the past 25 years. The third shock, when Iraq invaded Kuwait, was minor because Saudi Arabia greatly expanded production to compensate for the loss of Iraqi and Kuwaiti oil. It should be noted, however, that the probability of an oil price shock is not constant with time, but it increases as OPEC, and particularly core OPEC countries, increase their market share. As time goes on, the United States should be willing to pay more for insurance, in the form of R&D investments. Even when a price shock does not occur, oil-consuming economies may suffer economic losses if the oil cartel keeps prices above competitive market levels. This cost is also considered when estimating the insurance value of R&D (see below), and it seems more amenable to reduction by R&D than does the cost of the shock itself.

Greene (41) estimated the cost savings to the U.S. economy if technologies were developed that could double both the short- and long-term world price elasticities

TABLE 4   Potential value of R&D for reducing the cost of oil cartel pricing and oil price shocks (billions of current dollars)[a]

Value of doubling price elasticity of oil supply and demand		Probability of R&D success	Expected value of R&D, assuming 0.5 probability of a price shock	Annual willingness to pay for R&D
Price shock	No price shock			
555	373	0.10	46	6
555	373	0.25	116	15
555	373	0.50	232	30
555	373	0.75	348	45
555	373	1.00	464	60

[a]All values are discounted at a 5% annual rate. The assumed R&D investment is for 10 years. The scenario and analysis are those developed by Greene et al (12), which were based on a hypothetical oil supply curtailment in the years 2006 and 2007. Successful R&D is assumed to increase both the long- and short-term price elasticity of oil supply and demand, and the value of these changes is calculated for 1995–2010. The probability of R&D success is from 0.1 to 1.0, and the probability of at least one oil price shock over a 10-year period is assumed to be 0.5.

of oil supply and demand from 1995 to 2005.[2]   These savings are enormous. If a protracted oil price shock were to occur in the middle of the next decade, the present value of the savings to the U.S. economy is estimated to be ~\$550 billion, assuming a 5% discount rate and the scenario analysis methods of Greene et al (12). Even if no price shock were to occur, the increased elasticities of supply and demand would lead to more competitive, and therefore lower, world oil prices. Savings to the U.S. economy would still be an estimated \$370 billion because of the reduced costs of paying cartel-inflated prices. Savings from cartel pricing may already be evident—the current low price may be because of better exploration and production technologies.

Table 4 gives estimates of the potential cost savings for this risk for the effectiveness of R&D success (41). Even if the effectiveness of success is as small as $E = 0.1$, the annual willingness to pay or insurance value is \$6 billion/year for 10 years. The probability of an oil price shock over the next 10 years is taken to be $p = 0.5$. It derives from the fact that, over the past 25 years, there have been three shocks. If these events are independent, the probability of a shock was ~$p = 0.1$/year. Thus, the probability of a shock is $p = 0.68/10$ years, so we assumed $p = 0.5$ as a reasonable estimate for this time period. The value of insurance could be much higher if the probability of R&D success (its effectiveness) is >$E = 0.1$, integrated over 10 years.

Currently, the DOE spends ~\$0.7 billion/year on R&D relevant to this oil price shock risk (see Table 3). This investment is much less than what could be justified as prudent insurance (see Table 4). However, this value does not include

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[2]Price elasticities are dimensionless parameters economists use to measure how sensitive markets are to price changes. A price elasticity is precisely the percent change in quantity (supplied or demanded as the case may be) for a 1% change in price.

the private-sector investment, which includes the investments of the petroleum industry and the transportation industry. These latter investments are at least as large (1). The overall relevant investment is likely to be more than double the $0.7 billion/year spent by DOE.

Effective R&D will yield technologies that apply to both supply of and demand for oil (and substitutes) and that increase both short- and long-term price elasticity. The effects of doubling short- and longer-run elasticity of oil supply and demand worldwide are indicated schematically (Figures 1 and 2). Greene (41) describes two types of technology developments that might significantly increase price elasticity: (*a*) advanced automotive technologies such as those being developed through the PNGV and (*b*) technology for reducing the cost of alternative fuels. Nevertheless, it is probably fair to claim that DOE has not analyzed systematically the role that R&D can play to reduce the cost of an oil price shock and market manipulation by the oil producers' cartel. For example, there has

Figure 1 Schematic representation of world demand and supply of oil outside OPEC. If there were no cartel, price would be P_0 from the intersection of the world demand, $D_{w,1}$, and world supply without the cartel, $S_{row,1}$. The cartel supplies quantity Q_1 at a world price of P_1. The net demand curve for the cartel derives from the values of Q for various values of P, and these are plotted as D_1 in Figure 2. With better technologies that increase the price elasticities of both supply and demand by a factor of two, $D_{w,1}$ and $S_{row,1}$ are shifted to $D_{w,2}$ and $S_{row,2}$. The cartel sells Q_2 at P_2, a much lower price.

Figure 2   Schematic representation of the potential impact on the oil market of technologies that double the price elasticities of both supply and demand in the longer run. Improved technologies do two things. They reduce the world market price of oil and quantity supplied by the cartel in the longer run, and they reduce the magnitude of any price shock from a reduction in cartel supply. Technologies can reduce the slope of the marginal return and net demand curves of the cartel as illustrated by the change from point (p) 1 to point 2 along the cartel marginal cost curve, MC. The profit-maximizing price for the cartel with demand curve D_1 is at point 1, where the marginal revenue curve, MR_1, intersects MC. With demand curve D_2, caused by doubling price elasticities of supply and demand, the profit-maximizing condition is shifted to point 2. Price is reduced from P_1 to P_2 and the quantity supplied by the cartel from Q_1 to Q_2. A long-term reduction in cartel supply is represented by Q_1-q_1, and the consequential price rise is ΔP_1. The same reduction at point 2 causes a price increase, ΔP_2, half as large. Qualitatively the situation is similar for a short-term disruption if the short-term elasticity at point 2 is twice as large as for point 1, the same relative situation as for longer run elasticity. If a disruption occurs over the period of a year or less, the short-run demand curves for the cartel are much steeper, perhaps by a factor of 10, so the price rise caused by the disruption is much greater. However, the price shock at point 2 is much less than at point 1, although the slope of the demand curve at point 2 also increases by a factor of 10 in the short term.

been no comprehensive study of the technological options for increasing the price elasticity of supply and demand. Such an analysis was recommended by PCAST (4).

Urban Air Pollution

Estimates for the health costs of air pollution from vehicles alone are $20–300 billion/year (29). To be conservative, we have chosen the lower bound. Suppose that PNGV and other advanced energy technologies will reduce urban pollution by 20% in 10 years. The present-worth value of that savings (assuming a 5% discount rate) would be greater than $2 billion/year. Americans should be willing to pay up to this amount for R&D to invent the better technologies needed. In this case, the effectiveness of R&D is included in the 20% number in Table 1.

As shown in Table 3, DOE R&D investment relevant to this risk is ~$0.9 billion/year. Hence, the DOE investment seems well justified. It is also certain, however, that the private sector is investing at least as much as DOE to reduce the emissions from road vehicles and other energy sources because of government regulations. In fact, the DOE investment is often leveraged by the private sector, for example, in the case of PNGV. The DOE investment should result in less expensive ways to reduce emissions, as well as oil use. Thus the energy R&D investment is synergistic with that made by the private sector to meet regulations. Even after doubling the $0.9 billion/year, a larger national investment may be warranted.

Energy Disruptions

In this section, we concentrate on the electricity-supply system disruptions, although we recognize that the natural gas and petroleum systems are also vulnerable to disruptions. In all, electricity outages in the United States are estimated to cost >$26 billion/year (42). Blackouts of a few hours have been estimated to cost between $1 and $5/kWh (30). One estimate puts the cost of the New York City blackout of 1977—one of the most extensively studied outages from a cost point of view—at almost $350 million (30). Today that cost would likely be much higher. As another data point, until the derating of the California/Oregon Intertie after the western grid outages of 1996, energy customers in southern California were saving, on the average, $1 million/day by purchasing Pacific Northwest energy (43). The derating was made to avoid outages, and the cost to consumers of the added reliability was $1 million/day. Similar data for the cost of gas pipeline disruptions are not available. Data from the U.S. Department of Transportation, however, show that property losses from gas pipeline incidents from 1984 to 1994 were ~$340 million. Data on collateral damages are not known, but there is anecdotal evidence of businesses that have been shut down during natural gas delivery disruptions.

It is not clear what incentives deregulation will create for electricity providers to take steps to improve reliability, but it is not obvious that providers will be able to recover the full value of R&D investments. The benefit is captured by consumers,

but are there adequate mechanisms for them to pay the added cost? The role of government may be to encourage the necessary investment through regulations or other policies and to support or motivate the needed R&D. Similar arguments apply to other parts of the energy system.

If, over time, better and more resilient technologies [including enhanced systems monitoring, analysis, sensors, and control devices; advanced operating and maintenance techniques; improved and hardened information systems; new energy storage and generation (including on-site applications); expanded energy load management; and new materials] can be developed and put in place, society should be willing to pay some fraction of $26 billion/year to do the necessary R&D. In fact, all indications are that the cost and probability of disruptions are an increasing trend as the infrastructure ages and is asked to do more. Also, some small fraction of such outages in the future may be the result of sabotage or terrorism, and better technologies may reduce that risk. Suppose these better technologies may reasonably reduce the cost by 10%–30% or $3–9 billion/year in 10 years. The effectiveness of R&D success is arguably >10%, so at least $0.2–0.5 billion/year in R&D investment to invent cost prevention technologies seems justified in constant dollars.

In Table 3, the enumeration of R&D expenditures relevant to energy disruptions other than oil price shocks is estimated to be ~$0.4 billion for FY99. It should be mentioned that only a very small portion of this R&D is addressed exclusively or primarily to energy disruption. There is no systematic R&D program within DOE for this purpose.

THE SPIN-OFF VALUE OF R&D

The government investment in energy R&D seems to be warranted based on its insurance value, but it is likely to have social benefits even if the probabilities of the four risks turn out to be much smaller than estimated here. This is because the technologies developed as a result of the R&D are likely to have value no matter what happens. (Estimates of the societal rate of return for R&D vary widely but are between 20% and 100%.) [See the discussion in the report by the National Science Foundation (44).]

One risk to the U.S. economy is that it will not be competitive in the world market for energy technologies. Over the next 15–20 years, the market may grow to several trillion dollars per year (for the sake of argument, suppose it is $1 trillion/year). The profits on these sales might be as much as 20%, or $200 billion/year. If the U.S. market share can be 10%–20%, this would be $20–40 billion/year as U.S. profits. Suppose a 500% return on an energy investment is required, then the U.S. private sector should be willing to invest $4–8 billion/year to capture its share of the profits. Although not all of this profit would be directly from R&D, substantial R&D is required to capture this future market.

We leave this sort of risk to the "invisible hand" and the working of the "free" market. Some argue that competitiveness is no business of government except to ensure a level playing field and the "freeness of the market." Under these circumstances, the private sector surely can take care of itself. Nevertheless, one of the spin-off benefits of public sector investment in energy R&D as insurance against societal risks is that the economy is the benefactor—it becomes more competitive. After all, many other countries face the same risks, and if the United States is successful in developing better technologies for reducing these risks, those technologies are likely to be attractive in the global market. The technologies are also likely to be attractive to developing nations and, as such, will contribute to the development of the poorer countries of the world.

Another spin-off benefit is obvious but important. R&D success not only reduces the cost of risks, but it should markedly reduce the cost of or improve energy services to the U.S. economy. For example, one estimate is that the cost of reducing greenhouse gas emissions can be substantially offset by the reduced cost of energy services from using advanced, more efficient technologies (36).

MANAGEMENT NOTE

From the type of analysis presented here, a plausible and defensible answer may be supplied to the question of how much the government is justified in investing in energy R&D. Furthermore, this analysis should provide a basis for examining what the government is doing with respect to each risk and opportunity. This analysis should provide clues about what is missing and help prioritize programs. It should also provide a means for determining when enough has been done and where the investment can be decreased. Finally, it may provide a better means for explaining the need and rationale for government energy R&D programs in terms that are more understandable to the public and decision makers.

CONCLUSION

The value of R&D as an insurance investment to reduce the cost of the risks of climate change, oil price shock, urban air pollution, and energy disruptions is estimated conservatively to be more than $12 billion/year. However, the total that is justified is less than this sum because some R&D is applicable to more than one risk factor. For example, PNGV is, as mentioned, a highly relevant technology for reducing the cost of oil price shocks. It is also very important for climate change and indeed for urban air pollution. Consequently, in portioning the DOE budget, the transportation energy technologies (of which PNGV is a part) were counted fully for three of the four risks. In this way, the DOE R&D investment

in each energy technology area was given as much credit as possible for each risk area.

To estimate how much this overlap between risks might be, the present DOE portfolio (Table 3) was examined. The total energy technology R&D budget for FY99 is $1.5 billion, but the amounts relevant to the four risks were estimated to be $1.1, $0.7, $0.9, and $0.4 billion for climate change, oil security, air pollution, and energy disruptions, respectively, for a total of $3.1 billion. Thus, the ratio of the relevant amounts to the total budget is very close to 2:1. Assuming that this overlap is representative of that inherent in the technologies to mitigate the risks, the total value of $12 billion might be divided by two to obtain a value of $6 billion as justified as an insurance premium.

Our analysis suggests that the United States can justify spending more for R&D in the areas of climate change, oil price shocks, and urban air pollution. For climate stabilization, the justifiable R&D investment is probably at least $2 billion/year more. If we assume that the private sector is currently supporting relevant research comparable with the DOE investment, then at least $1 billion/year more seems justifiable. For oil price shocks and cartel pricing, private sector R&D investment is likely larger than that of the government. Thus, the total relevant national investment is likely >$1.4 billion/year, but still much below the range justified for insurance. For urban air pollution, a larger government investment could be justified even if the private sector investment is as large. The government investment relevant to energy disruptions seems closer to adequate, but there is no really comprehensive program in DOE. Therefore, the investment is likely not optimally deployed.

In this analysis, only the insurance value of the R&D investment was estimated. No credit was given to the value that may accrue to the economy because better technologies are marketed as a result of the R&D investment. It is notable that the PCAST Energy R&D Panel recommends that the government investment in energy technology R&D is inadequate— by ∼$1 billion/year— to meet the challenges of the 21st century (4). The PCAST conclusion was based on a bottom-up analysis of the DOE energy technology R&D portfolio, and it is completely different than the analysis presented in this paper.

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