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How Much is Energy R&D Worth?

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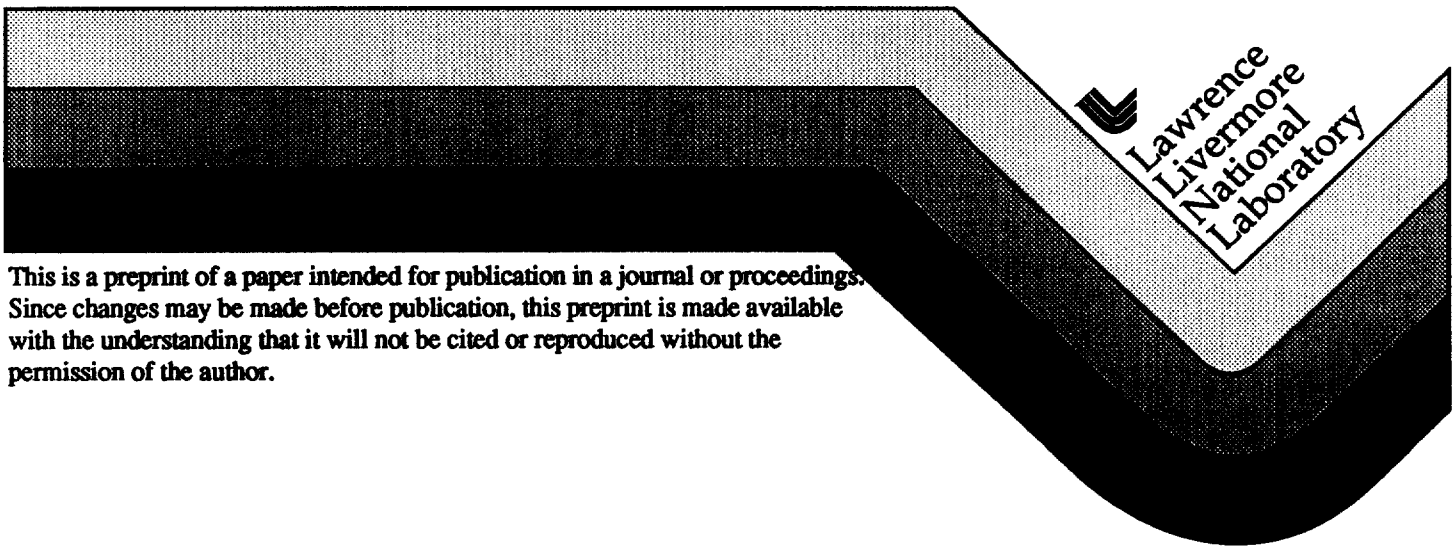

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ABSTRACT

The value of energy technology R&D as an insurance investment to reduce the cost of climate change stabilization, oil price shocks, urban air pollution, and energy disruptions is estimated to be $5–8 billion/year in sum total. However, the total that is justified is actually less than this sum because some R&D is applicable to more than one risk. Nevertheless, the total DOE investment in energy technology R&D (about $1.3 billion/year in FY97) seems easily justified by its insurance value alone; and, in fact, more might be warranted, particularly in the areas related to climate change and urban air pollution. This conclusion appears robust even if the private sector is assumed to be investing a comparable amount. Not counted is the value to the economy and to U.S. competitiveness of better energy technologies that may result from the R&D; only the insurance value for reducing the cost of these four risks to society was estimated.

INTRODUCTION

Over the past decade (1985–1994) the total U.S. investment in energy R&D (public and private) decreased from about $7 billion/year to $5 billion/year (in 1995 constant dollars) (Yergin et al., 1995, and Dooley, 1996). 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 (Dooley, 1997).

The United States spends about $550 billion/year for fuels and electricity. Thus, about 1% of energy costs are spent on R&D. The United States invests some $175 billion per year on all R&D, of which about $75 billion is federal, with more than half of that for defense. Thus, only about 3% of total R&D is spent on energy, although energy comprises at least 8% of GDP.

So what? Why should anyone care? After all, there is no energy crisis (and there hasn't been one for 17 years, if one excludes the very brief price excursion after the invasion of Kuwait in 1990); energy prices are stable and generally low; and most environmental insults from energy production and use are being reduced. Arguably this improved situation is the result, at least partially, of the development and deployment over the past two decades of better energy technologies.

But important risks remain, and energy seems too important to ignore, as Jack Gibbons, Assistant to the President for Science and Technology, has recently noted (Science and Government Report, 1996): "...But if you think about it, everything comes back to energy: our global environmental strategies, our national economy, local and regional air pollution, the notion of moving toward a more resource-efficient society, national security in terms of the Middle East, the burgeoning requirements of the Third World, especially the Asian rim—everything comes back to energy."

In what follows, four of these risks are described, and the potential for energy R&D to provide insurance to reduce the cost of the risks is discussed. The value of this insurance is estimated and compared to the current DOE energy technology R&D investments.[1] Successful R&D is a necessary means to reduce costs, but it is not necessarily sufficient for the full management of these risks. Other policies to stimulate R&D by the private sector or to encourage the early adoption of resulting better technologies may be needed as part of the insurance strategy.

WHAT ARE THE IMPORTANT RISKS TO SOCIETY FOR WHICH R&D CAN PROVIDE SOME INSURANCE?

Four risks are considered: climate change, oil price shocks, urban air pollution, and energy system disruptions other than

oil.[2] These are risks borne by society and as such are the concern of government. To the extent that the risks can be reduced by R&D, government should provide the necessary sponsorship or encouragement. The private sector alone is unlikely to carry out or sponsor the necessary R&D because it is unable to capture sufficient return on its investment in a reasonable time. Nevertheless, the private sector must be a partner with government if R&D is to be most effective at reducing the costs of risks.

Climate Change

Potentially adverse climate change caused by emissions of greenhouse gases, particularly CO_2 from the combustion of fossil fuels, is a hundred-year global problem. The extent and impact of temperature change is uncertain, as is the cost of mitigation (Lave, 1995). Nevertheless, should it prove necessary, mitigating climate change will have a profound effect on the energy systems of the world, which are 75% dependent on fossil fuels today. We are faced with either greatly curtailing the use of fossil fuels or finding ways to use them without putting CO_2 into the atmosphere. Recently, Wigley et al. (1996) have estimated the cost of optimally timed mitigation strategies for stabilizing the atmosphere at various levels of CO_2 concentrations. The 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 the atmosphere at 550 ppm(V) is about $1 trillion, discounted at 5%.

Subsequently, Edmonds et al.(1997) estimated that this cost could be reduced to nearly zero if certain advanced technologies were developed and deployed beginning in the 2015–2025 time period. These include non-fossil electric generation technologies producing electricity for less than $0.04/kW-hr, 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 for which energy technology R&D can make an enormous difference, and given the uncertainties about the risks, doing the R&D would seem to provide a 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(V) in 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.

An important debate is in progress as a result of the Wigley et al. (1996) analysis. One school suggests that the immediate action needed today is R&D to produce better technologies. The other school argues that one needs to force the reduction of CO_2 emissions now by measures such as a carbon tax (e.g., Grubb, 1996). Both sides agree, however, that R&D to produce better technologies is needed now. But one camp wants to force reductions immediately, and the other wants to delay, because forcing the system too soon is not the way to minimize overall costs of stabilizing at some particular CO_2 concentration. Those who believe the system should be forced now argue that such forcing will also stimulate R&D and innovation by the private sector.

Oil Price Shock

Monopolistic pricing of oil by the Organization of Petroleum Exporting Countries (OPEC) cartel has been estimated to have cost the U.S. economy some $4 trillion over the period 1973–1991 (Greene and Leiby, 1993). A substantial fraction of this loss occurred as a result of oil price shocks in 1973–74 and 1979–80 because of the Arab oil embargo of 1973–74 and the Iran-Iraq war of 1979–81. The losses to the U.S. economy included transfer of wealth to OPEC countries, decreases in the rate of growth of GDP, and costs resulting from non-optimum policies (Greene and Leiby, 1993).

Could such shocks happen again? Since 1986 OPEC, especially the Arab members of OPEC, have been regaining world market share. This is the condition that returns power for manipulating prices to a Stackelberg cartel (Greene et al., 1995, and Greene, 1996). It is the condition that concerns the community who worry about energy security (Martin et al., 1996) and will, because of the large amount of world oil reserves remaining in the Middle East, become more likely with time. Greene et al. (1995) model the behavior of OPEC and analyze the case of a short-term (two-year) oil supply curtailment of the same magnitude as occurred in 1973–74 or 1979–80. If this were to occur in the middle of the next decade when Arab OPEC's market share has risen to about 40%, the loss to the U.S. economy would be $500 billion, and Arab OPEC would gain about the same amount (Greene, 1996, and Greene et al., 1995). The Strategic Petroleum Reserve is not effective against such a large curtailment, but what might be effective are technologies that reduce oil use through efficiency improvements or more attractive replacements and increase the price elasticity of demand and supply. Such technologies are being developed by the Partnership for a New Generation of Vehicles (PNGV) among the automotive big three and the government, which aims to bring to market a cost-effective five-passenger car with 80-mpg fuel efficiency that does not sacrifice performance or safety.

We do not know what the probability or timing of another oil price shock are. Some believe the probability is very small (Bohi and Toman, 1996, and Lichtblau, 1994). Nevertheless, the cost of such a shock could be very large. Again, R&D to develop technologies to reduce these large costs may be inexpensive insurance.

As in the case of climate stabilization, other policies might be effective. One might be a tax on oil use or imports. If large enough, this would retard oil use and likely stimulate R&D or other strategies. 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 (GAO, 1996).

Urban Air Pollution

Much of urban air pollution is because of 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 larger than $10 billion/year, an estimate for the Los Angeles Basin alone (Hall et al., 1992, and Romm and Ervin, 1996). Estimates of air pollution costs for the whole country from motor vehicle emissions range from $20–300 billion per year. (See an excellent summary by McCubbin and Delucchi, 1996). Much is being done, and air quality in most U.S. cities is improving. Important weapons to assure continued improvement are cleaner and more cost-effective energy technologies. R&D is the price of these better technologies, and the pay-off 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 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 other states the sale of zero-emission vehicles is mandated by early in the next decade. No doubt these policies also act to stimulate R&D and innovation. These incentives complement government R&D programs.

Energy Disruptions

The U.S. energy infrastructure is remarkably resilient to disruptions. Disruptions do occur, however, generally related to natural phenomena such as weather. Disruptions can be expensive and even hazardous to human health and well-being. Because of regulatory changes likely to occur due to competition 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 U.S. 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 (Office of Technology Assessment, 1989). Recent events in the U.S., however, have caused speculation that physical terrorism might be on the rise in this country.

A growing dependence on communications and information management in energy delivery systems, however, 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, less so for distribution. To give some perspective on this dependence, one utility reported having 20,000 PCs, two mainframes, 460 LANs and a corporate database of 1.45 terabytes (Danielson, 1993). 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 growing 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, making access relatively difficult, they are probably not immune to attack. Plans by some utilities calling for the use of the Internet for energy brokering, communicating with customers in "real-time" (Hoffman, 1996) and other forms of electronic commerce will likely increase the vulnerability to this form of disruption.

Simultaneous attacks on control systems throughout a regional grid could be made by electronic and physical terrorists. Unfortunately, grid operators do not have the same degree of sophistication in tools and experience to deal with these forms of disruptions as for those caused by weather, for example. The consequences of disruptions caused by electronic tampering, consequently, have the potential to dwarf those from more conventional causes, like losing a major intertie because of grounding to a tree.

Perhaps the most pervasive, yet subtle, factors in energy delivery systems reliability are the impending pressures of competition and new regulatory requirements. Although electric loads have increased at about 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 a million dollars a mile, capital has also been a factor (Hoffman, 1996). Consequently, desires to increase asset utilization and cut costs can cause delivery systems to be operated much closer to their design limits and can thus raise the exposure to disruptions. This exposure is compounded because, with current technology, one rarely knows where the limit truly is.

Fortunately, there are a number of potential solutions for mitigating many energy delivery system reliability problems. Some of these involve the development of better 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.

HOW MUCH IS THE INSURANCE WORTH?

Here a rough estimate is 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. There is much uncertainty in the numbers. Conservatism was applied in the sense that the probabilities of losses are estimated on the low side of the range of uncertainty. The choices and calculations are exposed. Finally, the potential insurance value of R&D investments are compared with the actual FY97 DOE budget applicable to each risk area.

TABLE 1. THE INSURANCE VALUE OF ENERGY R&D INVESTMENTS FOR VARIOUS RISKS.

	Climate change	Oil price shock	Urban air pollution	Energy disruptions
Potential cost to U.S. (C)	25% of $1000B = $250B	$500B	>$20B/y	$26B/y for electricity disruptions alone
(times)				
Probability of incurring cost (p)	0.25 for 550 ppm(V) or less	0.1 cumulative total for next 10 years	1.0 (occurring now)	1.0 (occurring now)
(times)				
Effectiveness of R&D to reduce cost (E)	0.5–0.8	0.1–0.2 (conservative guess)	0.2 in 10 years (conservative guess)	10%×(10–30%)=1–3% in 10 years (conservative guess)
(equals)				
Insurance premium value of R&D (V)	**$2–3B/y for 15 years**	**$1–2B/y for 5 years**	**>$2B/y (discounted at 5%)**	**$0.2–0.5B/y (discounted at 5%)**
DOE's FY97 investment in R&D relevant to this risk (see Table 2)	$1B/y	$0.7B/y	$0.7B/y	$0.4B/y

For each risk we calculate the value as follows:

$$V=CpE \quad , \qquad \text{(Eq. 1)}$$

where V is the value of R&D as insurance, 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 cost. Table 1 summarizes the numbers used in this equation.

Climate Change

It is assumed, after Edmonds et al. (1997), that R&D can reduce the cost to world societies of stabilizing the climate at 550 ppm(V) by $1 trillion discounted net present value. Further, we assume that the probability of needing to stabilize at this level or below is 25%, so the nations of the world should be willing to spend at least $250 billion to obtain the needed advanced technologies to save $1 trillion. The investment would need to be made over the next 15 years, and the annual spending rate justified is hence $17 billion. The U.S. share in the investment, prorated at its current level of emissions is about 25%; thus the U.S. should be willing to invest up to $4 billion/year.

In this calculation the crucial number is, of course, the 25% assumed probability that the climate must be stabilized at 550 ppm(V) or less. The number can be rationalized but not justified. Clearly, the move by the United States and other OECD countries to set firm goals for emissions of greenhouse gases indicates the seriousness with which many view the risk (Wirth, 1996). The 25% number says that there is one chance in four that the world community will decide to stabilize emissions at 550 ppm(V) or less. If stabilization must occur at lower concentrations, the value of advanced technologies would be greater, but the time for development would be shorter. The reverse applies to the case where the stabilization concentration is greater than 550 ppm(V). For example, if stabilization at 450 ppm(V) were required, advanced technology would save three and a half times as much as for the 550 ppm(V) case, provided it was available 10 years earlier (Edmonds et al., 1997). If stabilization at 650 ppm(V) were required, advanced technology might save only one third as much, and the time for developing the technology would be stretched another decade or so.

The effectiveness of R&D we estimate to be somewhere between 0.5 and 0.8. We do this because we believe there is a high probability of technological success in the next 15 years, assuming that adequate investments continue to be made. That is, we think there is a good chance that non-fossil sources of electricity at less than $.04/kW-hr, biomass feedstocks in the range of $1.5–2.5/GJ, and fuel-cell-powered vehicles competitive with internal combustion vehicles are possible. To achieve these goals will require a determined and continuing effort. On this basis, the overall insurance value of this R&D is between $2 and 3 billion/year to the U.S.

The FY97 DOE energy technology R&D budget was analyzed for relevance to this climate change risk. The results are presented in Table 2. They indicate that in FY97 the DOE

TABLE 2. HOW MUCH IS ENERGY R&D WORTH: THE INSURANCE VALUE OF DOE INVESTMENTS (All budget amounts in $M)

Energy technologies or R&D area	FY97 Budget	Climate change		Oil price shock		Urban air pollution		Energy disruptions	
		Relevance	Budget share	Relevance	Budget share	Relevance	Budget share	Relevance	Budget share
Fossil Energy R&D	**368**	**varies**	**190.5**	**varies**	**254.5**	**varies**	**231.2**	**varies**	**56.8**
Coal, including clean coal	*118	varies	58.7	M-H	88.5	varies	102	L	23.6
Advanced clean fuels research	**16	L	3.2					L	3.2
Adv. clean/efficient power systems	**69	M	34.5			H	69	L	13.8
Advanced R&TD	**18	H	18			H	18	L	3.6
Clean coal	**15	L	3			H	15	L	3
Petroleum	*46	L	9.2	H	46	L	9.2	L	9.2
Misc. R&D (mining, cooperative, etc.)	*13	L	2.6						
Gas	*120	H	120	H	120	H	120	L	24
Natural gas research	**70								
Fuel cells	**50								
Program development & mgmt. support	*69								
Plant and capital equipment	*2								
Energy conservation	**400**	**~H**	**374**	**varies**	**333.5**	**varies**	**333.5**	**M**	**187**
Transportation	*175	H	175	H	175	H	175	M	87.5
Industry	*118	H	118	H	118	H	118	M	59
Buildings	*81	H	81	M	40.5	M	40.5	M	40.5
Policy & management	*26								
Renewables R&D	**265**	**~H**	**252**	**varies**	**116.6**	**varies**	**139.95**	**varies**	**169.9**
Photovoltaics	*60	H	60	L	12	M	30	H	60
Biofuels	*55	H	55	H	55	H	55	H	55
Solar building research	*3	H	3	L	0.6	H	3	M	1.5
Solar thermal energy	*22	H	22	L	4.4	L–M	7.7	L	4.4
Wind	*29	H	29	L	5.8	L–M	10.15	L	5.8
Renewable incentive program	*2	H	2	L	0.4				
Resource assessment	*1	H	1	L	0.2				
Solar and renewable energy deployment	*2	H	2	M	1	H	2	H	2
Geothermal	*30	H	30	L	6	L–M	10.5	L	6
Hydrogen	*15	H	15	H	15	H	15	L	3
Hydropower	*1	H	1	L	0.2	L	0.2	L	0.2
Electric energy systems and storage	*32	H	32	M	16	L	6.4	H	32
Policy and management	*13	H							

TABLE 2, Cont.

Energy technologies or R&D area	FY97 Budget	Climate change Relevance	Climate change Budget share	Oil price shock Relevance	Oil price shock Budget share	Urban air pollution Relevance	Urban air pollution Budget share	Energy disruptions Relevance	Energy disruptions Budget share
Renewables R&D, cont.									
Nuclear fission	**57**	**~H**	**42**	**L**	**11.4**	**L-M**	**19.95**	**varies**	**7.6**
Light water reactor	*38	H	38	L	7.6	L-M	13.3	L	7.6
Nuclear technology R&D	*0	H	0						
Univ. research reactor support, & misc.	*4	H	4	L	0.8	L-M	1.4		
Program direction and management	*15			L	3	L-M	5.25		
Nuclear Fusion	**233**	**M**	**116.5**						
Total energy technology R&D	**1323**		**975**		**716**		**724.6**		**421.3**
Office of Energy Research (not including fusion)	**1184**								
Basic energy science (BES)	*641								
Computational & technology research (CTR)	*154								
Biological & environmental research (BER)	*389								
TOTAL energy R&D incl. BES, CTR, and BER	**2507**								

Notes: 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 FY97 budget totals. Not included under fission is any part of the $382M for the Office of Civilian Radioactive Waste Management that is 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 $632M budget for the Office of Nonproliferation and National Security is included. Also, not included is $235M being spent on inertial fusion research associated with nuclear weapons by DOE Defense Programs. Some significant part of the budget of the Office of Energy Research is applicable as basic research support for the energy technologies, but allocation to each risk area is unknown.

* = included in total shown in bold above
** = included in category total above, marked with *
H = high relevance (We assume the whole budget counts for that particular risk.)
M = medium relevance (half the budget counts)
L = low relevance (0.2 of the budget counts)
Blank space = the R&D counts zero or is included in a higher-level total

was spending about $1 billion in mitigation-relevant research. An expenditure two to three times as large is justified on the basis of the above argument. Whether such an increase can be spent wisely and efficiently is another question, one that should be examined very carefully. Also, it should be noted that the government R&D investment often leverages a substantial matching contribution from the private sector, so the government investment underestimates the relevant total national effort. Recently, for example, the insurance industry worldwide is becoming increasingly concerned about ways to mitigate greenhouse gas emissions, including encouraging energy efficiency and R&D (Mills, 1996). It sees these measures as a hedge against natural disasters spawned by climate change. Still, there are significant R&D opportunities that are not being explored or that could be explored more aggressively.

Recently, Williams (1996) has suggested that fossil fuels can be used in a greenhouse-constrained economy that uses hydrogen to power vehicles. The idea may be feasible if fuel cells become the power source of preference for high-efficiency, high-performance vehicles, and if these create a demand for a hydrogen-fueled transportation sector. In a greenhouse-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 in depleted gas wells or deep saline aquifers. To examine this possibility, research on sequestering CO_2 is needed as well as more work on fuel cells and the thermochemical processes for producing hydrogen. This is R&D that could be added to the present DOE research agenda or be the justification for more intensive investment in areas already funded at some level. Another critical aspect of this possibility is the production of hydrogen from biomass, with and without sequestering. Work is needed on biomass and municipal solid waste gasification (Williams, 1997).

A second area where increased R&D might have significant promise is for improving the nuclear fission option. Here, more R&D might be directed at proliferation resistance, more fool-proof reactor safety, and cost reduction (Fulkerson and Anderson, 1996).

A third area is R&D focused specifically on technologies attractive to developing nations. Their choices will be crucial to mitigating this risk. An example might be the development of a small-scale biomass electric generator for rural electrification that is also cost-effective, efficient, and user-friendly and that can cogenerate electric power and process heat.

Oil Price Shock

The cost to the U.S. economy of an oil price shock could be half a trillion dollars, and it could occur any time after the Arab core of OPEC regains sufficient market share, which is likely to happen after the middle of the next decade (Greene, 1996). Suppose the probability of such a shock is 1% per year over the next 10 years (a cumulative probability of 0.1), then we should be willing to pay up to $50 billion over that period to avoid the loss of $500 billion. (The world has experienced three such shocks over the past 23 years, so that the probability could arguably be as high as 10% per year. The third shock when Iraq invaded Kuwait was minor, because Saudi Arabia greatly expanded production to compensate the loss of Iraq's and Kuwait's 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 Arab OPEC countries increase their market share. Thus we should be willing to spend more as time goes on.

As Greene (1996) points out, however, developing technologies that significantly reduce oil demand, or that increase the short-term price elasticity of demand or supply, will not be easy. If we conservatively assume R&D can reduce the cost by only 10 to 20% (i.e., the effectiveness of R&D is only 0.1 to 0.2), then we should be willing to invest up to about $0.5–1 billion/year over the next 10 years or $1–2 billion/year over the next 5 years. Here there is an implicit assumption that the better technologies resulting from R&D are also cost-effective and penetrate the market.

This estimate of insurance value is conservative in two respects. First, the assumed probability of a future oil price shock is on the low side. It could be as high as 0.7 (rather than 0.1) in the next decade if one assumed the experience of the past 25 years applies (e.g., ~10% per year probability of a shock). Second, the effectiveness of advanced technology was estimated on the assumed resulting reduction in oil use and increase in domestic supply, without taking credit for any increases in the short term price elasticities of supply and demand. Hence, the insurance value could be at least a factor of seven greater than assumed or $3.5 to 7 B/y over 10 years.

Currently, the DOE is spending about $0.7 billion/year on R&D that is relevant to this oil price shock risk, as indicated in Table 2. That this investment is close to what might be estimated as prudent insurance is perhaps not an accident. After all, the oil price shocks of the 1970s led to creating DOE in the first place. DOE estimated for the Government Accounting Office (1996) the reduction in oil use and the increase in domestic oil production that could result from DOE's R&D efforts as 2.9 million barrels of oil per day equivalent by 2010 or about 16% of current oil use. The cost of this R&D was about $0.8 billion in FY96. This is certainly consistent with the estimate from Table 2 and the assumption of 20% savings possible. It is probably a valid observation, however, that DOE has not looked systematically or strategically at the role that R&D can play to reduce the oil price shock risk. For example, there has been no study of the options for increasing the price elasticity of supply and demand.

It should also be noted that the cost of an oil price shock is assumed here to be roughly proportional to the amount of oil used in the economy. This is not right in detail, but it is a reasonable first approximation. Thus, if improved technologies reduce the use of oil the cost of the shock is assumed to be reduced proportionately. How elasticities change with the introduction of advanced technologies is not known, but the change will likely add to the effectiveness of R&D (Greene, 1996).

Again considerable private-sector R&D investment is relevant to this risk. The DOE investment often leverages that of private firms. The overall relevant investment is likely in the ballpark of double the $0.7 billion/year spent by DOE. (Yergin et al., 1995)

Urban Air Pollution

The range of estimates for the health costs of air pollution from vehicles alone is $20–300 billion per year (McCubbin and Delucchi, 1996). 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. Society 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.

From Table 2, DOE R&D relevant to this risk is about $0.7 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. In fact, the DOE investment is often leveraged by the private sector, as in the case of PNGV. Even with doubling the $0.7 billion/year, a larger national investment may be warranted.

Energy Disruptions

Here we concentrate on the electricity supply system, recognizing that the natural gas and petroleum systems are also vulnerable to disruptions. In all, electricity outages in the U.S. are estimated to cost over $26 billion/year (Hof, 1991). Blackouts of a few hours have been estimated to cost between $1 and $5 per kilowatt hour (Office of Technology Assessment, 1989). 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 dollars (Office of Technology Assessment, 1989). Today, that cost would likely be much higher. As another data point, until the derating of the California/Oregon Intertie, energy customers in southern California were saving, on the average, $1 million/day by purchasing Pacific Northwest energy (Hardy, 1996). 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. Based on data from the U.S. Department of Transportation, however, property losses from gas pipeline incidents from 1984 through 1994 were about $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 incentivise the needed R&D. Similar arguments apply to other parts of the energy system.

If over time better and more resilient technologies 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. 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 probability of R&D success is arguably greater than 10%, so at least $0.3–0.9 billion/year R&D investment to invent cost-prevention technologies seems justified.

In Table 2 the enumeration of R&D relevant to energy disruptions other than oil is estimated to be about $0.4 billion for FY97. 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 on the basis of its insurance value, but it is likely to pay off 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 social rate of R&D vary widely, but are in the range of 20–100% [see the discussion in the report by the National Science Foundation, 1996].)

One risk to the U.S. economy is that it won't be competitive in the world market for energy technologies. Over the next 15 to 20 years the market may grow to several trillion dollars per year (for the sake of argument say it is $1 trillion/year). The profit on this might be 20% or $200 billion/year. If the U.S. market share can be 10–20%, it would be $20–40 billion/year as U.S. profits. Suppose we require 500% return on energy R&D investment; then the U.S. private sector should be willing to invest up to $4–8 billion/year to capture its share of the profits.

Generally, we leave this sort of risk to the "invisible hand," the working of the "free" market, and some argue that competitiveness is no business of government except to assure a level playing field and the "freeness of the market." Under these circumstances, the public 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 or may be the benefactor in that it becomes more competitive. After all, many other countries face the same risks, and if the U.S. is successful in developing better technologies for reducing these risks, those technologies are likely to be attractive in the global market. They 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 energy services to the U.S. economy.

MANAGEMENT NOTE

From this sort of analysis, perhaps a plausible and defensible answer can be derived 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 should provide clues about what is missing and what is being done that is less important. It should also provide a means for determining when enough has been done and 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 greater than $5–8 billion/year in sum total. However, the total that is justified is less than this sum because some R&D is applicable to more than one risk. For example, PNGV is, as mentioned, a highly relevant technology to reducing the cost of oil price shocks. It is also very important for climate change and indeed for urban air pollution, and even somewhat for energy disruption risks. 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.

Nevertheless, the United States can probably justify spending more in the areas of climate change and urban air pollution and perhaps for oil price shocks. For climate stabilization the justifiable investment is probably $1–2 billion/year more. If one assumes that the private sector is currently supporting relevant research comparable to the DOE investment, then up to $1 billion/year more is probably justifiable.

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.

Notes

1. Calling this investment in R&D an insurance premium seems a reasonable but not perfect 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. 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 "insurance" is the term used in this paper.
2. The four risks discussed here are not a comprehensive set. They are important and represent situations where 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.

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References

Bohi, D.R., and Toman, N.A., 1996, *The Economics of Energy Security*, Kluwer Academic Publishers, Boston.

Dooley, J.J., 1997, "Unintended Consequences: Energy R&D in a Deregulated Energy Market," draft submitted to *Energy Policy*.

Dooley, J.J., 1996, *Trends in US Private-Sector Energy R&D Funding 1985–1994*, Pacific Northwest National Laboratory Report PNNL-11295 UC400.

Danielson, J., 1993, "Electric Utilities' Computational Needs: Real Time Pricing and Distribution in the 1990's," presented at the *Energy Daily* and Pacific Gas and Electric Company Conference, San Francisco, CA.

Edmonds, J., Dooley, J., and Wise, M., 1997, "Atmospheric Stabilization and the Role of Energy Technology," to be published.

Fulkerson, W., and Anderson, T., 1996, "World's Energy Appetite May Crave Nuclear Power," *Forum*, 11, pp. 96–101.

General Accounting Office, 1996, *Energy Security: Evaluating U.S. Vulnerability to Oil Supply Disruptions and Options for Mitigating Their Effects*, General Accounting Office Report GAO/RCED-97-6.

Greene, D.L., 1996, "Consequences of U.S. Oil Dependence," *Energy*, Nov., p. 3.

Greene, D.L., et al., 1995, *The Outlook for U.S. Oil Dependence*, Oak Ridge National Laboratory Report ORNL-6873, Oak Ridge, TN.

Greene, D.L., and Leiby, P.N., 1993, *The Social Costs to the U.S. of Monopolization of the World Oil Market, 1972–1991*, Oak Ridge National Laboratory Report ORNL-6744, Oak Ridge, TN.

Grubb, M., 1996, "Technologies, Energy Systems, and the Timing of CO_2 Emissions Abatement: An Overview of

Economic Issues, Energy and Environment Programme," Royal Institute of International Affairs, London SW1Y 4LE, United Kingdom, submitted to *Energy Policy*.

Hall, J.V, et al., 1992, "Valuing the Health Benefits of Clean Air," *Science* **255**, pp. 812–817.

Hardy, R., Administrator, Bonneville Power Administration, 1996, Testimony before the Subcommittee on Water and Power Resources of the House Committee on Resources, Nov. 7.

Hof, R.D., 1991, "The 'Dirty Power' Clogging Industry's Pipeline," *Business Week*, Apr. 8, p. 82.

Hoffman, S., 1996, "Enhancing Power Grid Reliability," *EPRI Journal*, Nov./Dec., pp. 6–13.

Lave, L., 1995, "Greenhouse Scenarios to Inform Decision Makers," Ch. 50 in *The State of Humanity*, ed. by J.L Simon, Blackwell Publishers, Inc., Cambridge, MA, pp. 555–575.

Lichtblau, J.H., 1994, "Oil Imports and National Security: Is There Still a Connection?" *The Energy Journal*, Vol. 15, special issue, pp. 329–346.

Martin, W.F., et al., 1996, *Maintaining Energy Security in a Global Context, A Report to the Trilateral Commission*, New York.

McCubbin, D.R., and Delucchi, M.A., 1996, *The Social Cost of the Health Effects of Motor-Vehicle Air Pollution*, Report #11 in series: The Annualized Social Cost of Motor-Vehicle Use in the United States, based on 1990–1991 Data, University of California at Davis report UCD-ITS-RR-96-3 (11).

Mills, E., 1996, "Energy Efficiency: No-Regrets Climate Change Insurance for the Insurance Industry, Research Review," *Journal of the Society of Insurance Research*, IX, No. 3, p. 21.

National Science Foundation, 1996, *Science and Engineering Indicators—1996*, National Science Board, Government Printing Office, Washington, DC, NSB 96-21.

Office of Technology Assessment, 1989, *Physical Vulnerability of Electric Systems to Natural Disasters and Sabotage*, OTA Report to Congress of the United States.

Romm, J.J., and Ervin, C.A., 1996, "How Energy Policies Affect Public Health," *Public Health Reports*, Vol. 111, No. 5, Sept.–Oct.

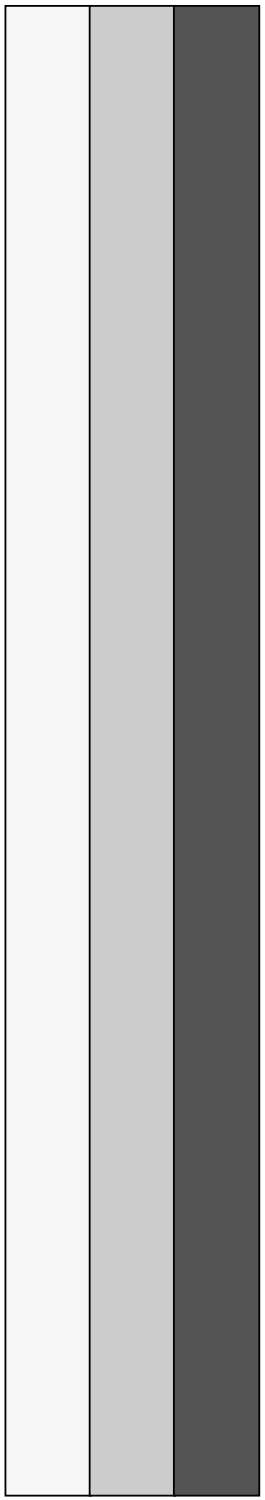
Science and Government Report, 1996, Vol. 26, Nov. 1, 1996.

Wigley, T.M.L., Richels, R., and Edmonds, J.A., 1996, "Economic and Environmental Choices in the Stabilization of Atmospheric CO_2 Concentrations," *Nature*, 379: pp. 240–243.

Williams, R.H., 1996, *Fuel Decarbonization for Fuel Cell Applications and Sequestration of the Separated CO_2*, PU/CEES Report No. 295, Center for Energy and Environmental Studies, Princeton University.

Williams, R.H., 1997. "A Strategic Analysis of Hydrogen Production R&D Priorities," Paper Review Draft, Center for Energy and Environmental Studies, Princeton University.

Wirth, T., 1996, Statement by Under Secretary of State for Global Affairs at the Second Conference of the Parties to the Framework Convention on Climate Change, July 17, Geneva, Switzerland.

Yergin, D., et al., 1995, *Energy R&D: Shaping our Nation's Future in a Competitive World: Final Report of the Task Force on Strategic Energy Research and Development*, Secretary of Energy Advisory Board, US Department of Energy, Washington, DC.

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