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TECHNOLOGY POLICY FOR ENERGY AND CLIMATE CHANGE

Lessons from a retrospective of thirty years on research, development, and demonstration experiences

Robert C. Marlay and Burton H. Koske

Dr. Robert C. Marlay is Director, Office of Science and Technology Policy, and Deputy Director, U.S. Climate Change Technology Program, Office of Policy and International Affairs, U.S. Department of Energy, Washington, DC 20585. The views expressed here are his own and not necessarily shared by the DOE or the U.S. Government.

Mr. Burton H. Koske, is an Advisory Engineer, Systems and Decision Science, Idaho National Laboratory, 955 L'Enfant Plaza, Washington, DC 20024. The views expressed here are his own and not necessarily shared by the Idaho National Laboratory or the U.S. Department of Energy.

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Lessons from a Retrospective of Thirty Years on Research, Development and Demonstration Experiences

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Increasing accumulations of carbon dioxide (CO_2) and other greenhouse gases (GHGs) in the Earth's atmosphere have raised concerns about the potential for climate change and related consequences[1]. These concerns have heightened attention to GHG emissions and the various means for their mitigation. If substantial reductions in anthropogenic emissions of GHGs were to be required over the course of the 21st Century, fundamental changes would need to take place in the way the world produces and uses energy, as well as in many other GHG-emitting aspects of industry, agriculture, land management and use, and other activities associated with modern civilization.

New and advanced technologies could enable and facilitate a gradual, long-term transformation to a future society characterized by significantly lower GHG emissions. Progress could be made by providing improved and less costly means for reducing, avoiding, capturing and sequestering GHG emissions, while also providing the energy and other services needed to sustain expanding economic activity and serve the rising aspirations of a growing world population.

It is generally agreed that certain policies aimed at stimulating technological innovation toward this end, including investment in research, development and demonstration (RD&D), constitute an important component of any long-term strategy aimed at addressing climate change. Beyond RD&D, however, there appears to be little agreement as to the answers to two key questions:

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[1] This paper was prepared for and presented at a workshop on "Technology Policy for Climate Change Mitigation – A Transatlantic Perspective", co-hosted by Resources for the Future, Washington, DC, and the French Center on the U.S. at IFRI (Paris), 16-17 December 2004, Paris, France. The workshop was supported by the French Ministry of Ecology and Sustainable Development (MEDD) and BP, PLC.

1. Might augmenting policies, beyond RD&D, be justified today to spur technology development and adoption?
2. If so, what does history suggest about the kinds of policies that might be most appropriate, and to what extent would they be applicable?

This paper attempts to provide insights to the answers to these two questions. It notes in passing the current state of climate change science and its uncertainties, which suggests the potential efficacy of so-called "hedging strategies" to reduce risk. It explores in some depth the "lessons" of various historical experiences (1970s to present), mainly from the United States, regarding various programs and policies intended to spur technology development and adoption, including both successes and failures.

CURRENT POLICY CONTEXT

Regarding the current state of affairs of the climate change issue, perhaps agreement can be reached on some elements, which may help frame a context for policy discussion:

As signatories of the United Nations Framework Convention on Climate Change (UNFCCC), more than 180 nations, including the United States, share its ultimate objective, that is, the stabilization of GHG concentrations in the atmosphere at a level that prevents dangerous interference with climate system. Climate change is an important global concern. All nations have a stake in addressing it appropriately.

- It is not known today what GHG concentration level may be "safe," or to whom. This issue remains a key policy and planning uncertainty. Even so, mathematically, it can be inferred that the "stabilization" of GHG concentrations at any level means that global *additions* of GHGs to the atmosphere and global *withdrawals* of GHGs from the atmosphere must come into balance. In order to achieve such stabilization, *net* global emissions of GHGs would eventually need to slow in growth, peak, and then decline until, ultimately, they approached levels that are low or near zero.
- Should the science so justify, the ultimate goal regarding emissions would always be the same – low or near zero. The direction and magnitude of the challenge for

technology to meet this goal are clear. Within this construct, only the timing of the actions that may be required is uncertain. For technology to make meaningful differences "at scale," much progress will be required. Part of this progress is learning by doing, so early technology adoption may be an important component of an overall technology development approach.

- Since no country or multi-country region can be expected to effect sufficient progress by itself, a role for international diplomacy is to build consensus for cooperative action around commonly shared goals. Because grounds for consensus are not settled, but evolving, it is important to identify policies that are appropriate for each point in time as these grounds change, while also reserving options to enhance or refine such policies over time. As new knowledge emerges and circumstances change, such policies can change.
- Advancing technology can have profoundly transforming effects over the longer term on the attainment of, or progress toward, important social or strategic goals.[2]
- The long-term nature of climate change requires a century-long global perspective. One-hundred year scenarios analyses suggest that the timing for large-scale adoption of advanced technology is an important, but not necessarily urgent, planning consideration. Allowing for capital stock turnover and other inertia inherent in a global energy system, technologies with low or near-net-zero GHG emissions profiles would, depending on the varying scenarios, need to be commercially available and moving into the marketplace over a range of time periods, dating from 2020 to 2070. There may be more urgency for technology development, however, given that new and advanced technologies often require long periods of effort in order to ensure readiness when, and if, needed.

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[2] See Constable, G., and Somerville, R., *A Century on Innovation – Twenty Engineering Achievements That Transformed Our Lives*, copyrighted by the National Academy of Sciences, Joseph Henry Press, 2003.

MIGHT AUGMENTING POLICIES BE JUSTIFIED TODAY TO SPUR TECHNOLOGY ADOPTION?

Turning to the first question, the answer, it would seem, depends on the certainty with which one regards: (a) the extent of the linkages between human-activities to climate change (the human-induced component of climate change versus natural variations); (b) the risks and consequences of the resulting climate change; and (c) the degree to which one imagines future options may be foreclosed by not adopting augmenting measures earlier rather than later.

If linkages are clear, risks great and options being foreclosed, costly and disruptive action would likely be justified. On the other hand, if linkages are uncertain and possibly weak, risks unclear, diffused or distant, and options not being foreclosed, then costly and disruptive actions might not be justified until more is known. Additionally, the costs and benefits of delay would need to be weighed against costs and benefits of early action.

There is general agreement about some facts.[3] Over the last 100 years, temperatures near the Earth's surface have varied, warming early in the 20th Century, cooling during mid-Century, then warming for the latter part of the Century. The current warming period is effecting observable changes throughout nature, evidenced by longer growing seasons and many other measures.[4] The opposite was true during the mid-Century period. GHGs are known to contribute to global warming through their ability to absorb infrared energy radiating from the Earth's surface, resulting in radiative forcing.[5] Overall, atmospheric concentrations of GHGs are increasing and human activities are largely responsible for these increases. Climate models forecast future temperature increases, which raise concerns. But, these models cannot predict with confidence how much climate change is attributable to human activity, or to natural

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[3] See National Research Council, *Climate Change Science: An Analysis of Some Key Questions*, Committee on Science of Climate Change, National Academy Press, Washington, DC, 2001.

[4] See Parmesan, C., and Galbraith, H., "Observed Impacts of Global Climate Change in the U.S.", prepared for the Pew Center on Global Climate Change, November 2004.

[5] Radiative forcing is a measure of the overall energy balance in the Earth's atmosphere. It is zero when all energy flows in and out of the atmosphere are in balance. If there is a difference, it is usually expressed in terms of watts per square meter (W/m2), averaged over the surface of the Earth. When it is positive, there is a net "force" toward warming, even if the warming itself may be slowed or delayed by other factors, such as the heat-absorbing capacity of the oceans or the melting of large natural ice sheets.

variation,[6] or to what extent other climate change dynamics might add or detract from such warming. Finally, the consequences of climate change are not well understood, nor geographically predictable.

Such uncertainties leave decision-makers unclear about the costs and benefits of various courses of action, or inaction. Humans might be able to slow the growth of, or reduce, anthropogenic GHG emissions at various rates, at various costs, but it is not certain to what extent climate change might be slowed or averted, what consequences might be mitigated or avoided, or what benefits might be realized, or by whom, such that they would justify or offset costs incurred.

When faced with potentially serious but uncertain risks, and when the benefits of the remedies are unclear, the situation usually calls not for "no-action," but for "hedging strategies." Hedging strategies offer some protection against future outcomes, prevent foreclosure of options, and cost less. If the costs of such strategies are largely internalized by governments, economic activity may proceed with minimum disruption. Complementing hedging strategies, other actions can be taken to work to reduce decisional uncertainties and further lower overall costs of anticipated remedies. As uncertainties narrow and costs fall, hedging strategies could be replaced by others, or enhanced, depending on what circumstances may be revealed in the future.

One such approach is outlined by Abraham.[7] It consists of: (1) near-term options that make sense today; (2) investments in science to reduce uncertainty and better inform future decision making; (3) investments in technology development to create new, transformational options for the future and to reduce their costs; and (4) constructive engagements in international settings wherever productive relationships can be established. In the United States, these elements are complemented by an array of Federal tax and financial incentives designed to spur innovation and technology adoption. Such policies are further complemented by state, regional, and local

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[6] Natural variables influencing the Earth's climate, include (1) solar variability, which can affect heat input to the Earth's environment. Recent research suggests high solar activity over the last 35 years, compared to the past 11,500 years. Also, there are (2) volcanic eruptions (CO_2, CH_4 and SO_2). Additionally, there are (3) variations in the elliptical shape of the Earth's orbit around the sun; the (4) tilt of the Earth's axis due to wobble; and (5) gyroscopic precession. Ice ages are tied to these variations. The Earth is now in a long warming period following the last ice age of about 11,000 years ago. These natural variables do not include other potentially important natural variables, such as (6) variations in surface and deep ocean currents and (7) geologic out-gassing of methane from seabed hydrates, due to earthquakes, landslides, etc. Over geologic time, these are believed to have influenced the Earth's climate.

[7] Abraham, S., Science, Vol. 305, 30 July 2004.

inducements to spur technology adoption. Although no specific "price" is affixed to an amount of CO_2 avoided, a price may be inferred from such actions and it is non-zero.

WHAT DO THE LESSONS OF HISTORY SUGGEST ABOUT THE KINDS OF AUGMENTING POLICIES THAT MIGHT BE MOST APPROPRIATE UNDER A HEDGING STRATEGY?

History shows that advancing technology, particularly when combined with well designed and visionary supporting policy, can have profound effects on the attainment of, or progress toward, important social or strategic goals. Advancing technology may be seen as relatively slow day to day when compared with more direct approaches such as regulation, taxes or other interventions, but nonetheless powerful in final effect over the longer term. Additionally, technology strategies are often found to be more broadly acceptable in terms of building consensus for political action. If not done well, however, the same tools can result in highly visible and expensive failures.

Examined below are 11 cases of technology and supporting policy approaches used over the past 30 years, mainly in the United States, in attempts to spur technology development and accelerate progress toward the attainment of important strategic goals. They include both successes and failures. The paper concludes by drawing summary insights from these cases histories.

1. Oil Exploration and Production (Success)

In the 1970s, in view of the oil market disruptions of the Arab embargo of 1973-1974, and of the Iranian Revolution of 1978-1979, energy security was of paramount concern. Accordingly, a strategic goal, which remains today, was to diversify the world's production of oil, in part, by enhancing the economic production of oil in geologic regions outside the producing areas known to be exposed to high risk and political tension, such as the Persian Gulf and the Middle East.

The U.S. supported RD&D in oil exploration and production that eventually resulted in an array of new science and advanced technologies. Upon adoption and further enhancement by private interests, these technologies revolutionized the means by which oil was discovered and produced. Now in routine commercial practice, these technologies include: (a) computer modeling and mathematical interpretations of seismic signals, enabling the characterization of oil and gas reservoirs in three dimensions (3-D seismic), and over time, in 4-D; (b) polycrystalline diamond drill bits, now an industry standard in key application areas, allowing well depths up 7,000 meters and reducing drilling times and costs by as much as 85 percent; (c) down-hole telemetry, enabling guided horizontal and multidirectional drilling; and (d) a variety of reservoir characterization and advanced oil recovery techniques.[8]

These advances emerged simultaneously with favorable results from other, coordinated policies, such as diplomatic and trade initiatives aimed at opening investment opportunities in areas previously closed to foreign investors. The combination of technology and policy had the effect of increasing global exploration and production by reducing the cost and improving the likelihood of finding and producing oil in certain regions of the world, which otherwise would have remained less, or marginally competitive with those in higher-risk oil production regions.

The result today is that these technologies have lowered costs and are now used to discover and recover new, rejuvenated, or expanded oil reserves throughout Asia, South Asia, Central Asia, the Caspian, Africa, Latin America, South America, and in some of the older producing regions of the United States. Global diversification of oil production was enabled and continues.

2. Synthetic Fuels (Failure)

Several strategic benefits were imagined for synthetic fuels during the “energy crises” of the 1970s. If successful, synthetic fuels from coal or shale could provide protection against future shortages or interruptions in the supply of oil. In the 1973-1974 disruption, oil shortages had proven to have a significant negative effect on the economy and, in extreme cases, could even affect national security. Second, synthetic fuel production might reduce the rate of future OPEC price increases. This would improve the U.S. balance-of-payments position and would provide some relief from

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[8] *Investments in Fossil Energy Technology,* Office of Fossil Energy, U.S. Department of Energy, Washington, DC, March 1997.

inflationary pressures. In addition, a unique advantage of synthetic fuel production is that it would provide information about the feasibility and costs of alternative technologies, which would be helpful in designing our long-term transition to alternative energy resources.[9]

On June 30, 1980, President Carter signed into law the Energy Security Act (ESA), which initially authorized $20 billion to stimulate the production of synthetic fuels based on the extensive domestic coal and shale resources. The Synfuels Corporation created by ESA was given the goal of achieving production of 500,000 barrels per day and 2,000,000 barrels per day by 1987 and 1992 respectively. It was clear at the time that those production levels could only be reached by some form of government subsidization of private sector activities.

The synfuels program was different from traditional RD&D activities and from prior Federal energy research. Synfuels development was to proceed to commercialization and was to be accomplished in the private sector with development-specific subsidies from the Synfuels Corporation. The Corporation was set up differently from other federal agencies. The salary structure was different and higher than the Civil Service. The initial appropriation of $20 billion was approved without any requirement for the Corporation to submit to the discipline of annual authorization and appropriation. Projects could be stimulated by production price guarantees, direct loans, and loan guarantees. Projects could be selected by competitive response to solicitation and by direct bilateral negotiation under certain circumstances.

The Corporation issued 12 separate solicitations of proposals for financial assistance to aid the construction and/or operation of synthetic fuels projects. In response to these solicitations, there were 204 specific proposed projects. This process ultimately led to only two working plants producing synfuels. The two projects, which were developed de novo by the Corporation, were the Cool Water Coal Gasification project and the Dow Syngas Coal Gasification project. Both of these projects produced medium Btu gas, which was subsequently burned to produce electricity. The gasification processes in both projects were new technology and proved to be technically feasible (see IGCC Case Study). In neither case did the technology lend itself to a broad application to produce a synfuels backstop.

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[9] Alice Rivlin, Director, Congressional Budget Office, Testimony before the Banking, Housing and Urban Affairs Committee, U.S. Senate, July 26, 1979.

The Synfuels Corporation lasted five and one-half years and was able to stimulate continuing production of synthetic fuels in only four projects. In 1984, after a controversy involving alleged conflict of interest, the President of the Synfuels Corporation resigned. His resignation left the Corporation with less than the required quorum necessary to approve projects. Appropriated funds available to the Corporation were cut to $8 billion and the production goals of the enabling act were eliminated. On December 19, 1985, the Synfuels Corporation was closed, with the residual responsibility to manage the Federal role in the existing projects transferred to the Treasury Department. All of this occurred during a period of rapidly declining energy prices.

Evaluated against its original goals, the Synfuels Corporation is to be judged a failure.[10] It did not establish a technology that would provide a synthetic fuel backstop to influence world energy prices. It developed only a small portion of the technical frontier, displaced little imported oil, and was slow in doing either. It is only fair to observe that even the best managed efforts would probably have failed to develop larger-scale synfuels production because of global circumstances changed, oil supply became abundant, the cartel collapsed, and energy prices fell from 1982 through 1985.

3. Coal Bed Methane (Success)

The case of coal bed methane (CBM) illustrates a more carefully tailored and coordinated program of technology RD&D (1978-1992), complemented by limited tax incentives (1980-1992), that resulted in an infant industry that in time became largely self-sustaining.

During the natural gas shortages of the 1970s, there was a widespread view that the resource base of natural gas in the United States was substantially depleted. A variety of non-conventional sources, including coal-bed methane, were considered possible sources of commercial gas. With a combination of basic and applied research, field demonstrations, and tax credit incentives, many of these non-conventional sources of natural gas now compete with conventional sources and contribute significantly to

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[10] Darius Gaskins, KSG and Bruce Stram, ENRON Corporation, “A Meta Plan: A Policy Response to Global Warming,” CSIA Discussion Paper 91-3, Kennedy School of Government, Harvard University, June 1991.

the nation's gas supply. In 2001 Coal-bed methane (CBM) supplied 1.56 Tcf annually, or 7.8 percent of domestic production of natural gas.[11], [12], [13]

Early work on CBM was carried out by the U.S. Bureau of Mines and focused on safety issues and pre-draining and capturing methane from the active, gassy mines of the Appalachia and Warrior basins. The Bureau of Mines program was assumed by DOE in 1978 and funded for five years. Subsequent R&D was conducted chiefly by the Gas Research Institute (GRI) and industry. The continuing DOE effort was aimed mostly at defining the size and recoverability of the resource base as well as the use of natural gas associated with active coal mine operations. Several pilot field projects were conducted, including testing the use of vertical wells in deep, unminable coal beds; testing the use of vertical wells in multiple coal beds; and combining in-mine, multiple horizontal boreholes and CBM-fueled gas turbines for on-site power generation. Experiments in hydraulic fracture stimulation, conducted by the Bureau of Mines and later by DOE, demonstrated the utility of this technology in CBM recovery. In addition to the DOE program, the DOE Small Business Innovative Research program funded several projects involving strategies for well-site selection, drilling practices, and well-completion techniques for coal-bed methane production. The GRI program continued into the 1990s.

In 1980, Congress enacted a tax credit to promote domestic production from alternative sources, including CBM. Known as the Section 29 tax credit (section 29 of the 1980 Crude Oil Windfall Profit Tax Act), the requirement had two limits: (1) the gas needs to be sold to an unconnected group, and (2) the tax credit could only be applied to wells brought on line before Dec 31, 1992. The credit, valued at $3 barrel of oil or Btu equivalent, ended on December 31, 2000, however the tax credit was modified and extended in both the House and Senate energy bills that the two chambers passed in 2001 and 2002, respectively.

For nearly a decade, little effect was seen from these twin measures of technology R&D and tax incentives. As recently as 1982, production from CBM was virtually nonexistent. Building on Federal advances, in 1983 the Gas Research Institute started a

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[11] *Annual Energy Outlook 2003,* DOE Energy Information Administration, DOE/EIA-0383 (2003), January 2003.

[12] Bezdek, Roger H., President, Management Information Services, Inc., *An Energy Policy That Actually Worked,* News and Issues, American Independent Producers Association, August 2002.

[13] *Coal Bed Methane Primer,* ALL Consulting and the Montana Board of Oil and Gas Conservation prepared for the National Energy Technology Laboratory, U.S. Department of Energy, February 2004.

number of field investigations that motivated expansion of CBM. Combined with a practical means to fracture and extract methane from coal seems, and a limited but important production tax incentive, CBM took off. By 1994, there were more than 6,000 producing wells; by 1999 more than 14,000. In FY 2003, the total estimated revenue loss (tax expenditure) associated with all of the Section 29 credits, including CBM, shale gas, biogas, and coal synfuels, was about $1.0 billion per year.[14] Since 1992, the tax incentives for new wells does not exist, but together with basic and applied research, the initial incentives were able to establish an industry that is now thriving, both in lean and better years. Today, the market value of methane is sufficient to stimulate expansion of this industry.

4. Wind Power (Success)

The Production Tax Credit (PTC), enacted in 1992, initially provided a 1.5 cent per kilowatt-hour credit, and currently provides a 1.8 cent per kilowatt-hour credit (adjusted periodically for inflation), for electricity produced from a wind farm during the first 10 years of its operation. This credit, along with continuing advances in technology, has yielded a robust and growing wind industry, and the fast-growing source of new power production in the United States. The production tax credit is an important feature for this technology, as evidenced by disruption its lapse creates. A two-year PTC extension (through December 31, 2005) was signed into law on October 4, 2004. The new provision also expands PTC eligibility to solar, geothermal, small irrigation hydroelectric power, open-loop biomass, refined coal, agricultural livestock waste nutrients, municipal solid waste and landfill gas.

Originally enacted by Congress as part of the Energy Policy Act of 1992, the PTC has expired and been renewed three times since its inception, each time with significant impacts to the wind power industry in the U.S. From 1998 to 2003, the amount of clean power generated from wind in the U.S. tripled, in part, to improvements in large-scale wind turbine technology, but primarily to the PTC. In spite of the policy bumps, over the last five years (1999-2003), U.S. wind generating capacity has expanded at an annual average rate of 28%. The American Wind Energy Association reports installed

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[14] Salvatore Lazzi, Resources, Science and Industry Division, *Energy Tax Policy*, Updated July 20, 2004, (Code IB10054), Congressional Research Service, 2004.

U.S. wind capacity for 2003 at 6,374 MW,[15] with utility-scale wind turbines installed in 30 states. One company, GE, recently announced new wind turbine contracts totaling an additional 2.5 gigawatts. Current estimates of Federal revenue losses (tax expenditures) for the PTC for wind and other renewable technologies are $355 million, as projected for 2005.

5. Brazilian Alcohol Fuels (Failure)

During the world energy crises of the 1970s, Brazil developed a large domestic industry producing alcohol from sugar cane and resulting in a substantial conversion of its automobile fleet to alcohol fuel. The analysis of this policy illustrates a rapid expansion of a limited government policy, initially established as a response to a perceived crisis, which was then propelled by rent-seeking interests far beyond its original scope, and with little consideration of its costs or effectiveness. Further, such programs are almost impossible to curtail once significant private investment has been made.

Brazil's alcohol program began in 1975 in response to two economic blows to the Brazilian economy. The price and volume of sugar, Brazil's major export, had fallen sharply, and the price of imported oil had quadrupled. The initial phase of the program consisted of subsidies to build distillery capacity at existing sugar mills to produce alcohol, and price subsidies to induce further use of alcohol as a blended component of automobile fuel. The fall in Brazilian sugar exports created substantial excess capacity and economic distress in the sugar industry. Brazil had extensive experience with the use of alcohol-blended fuel and it could displace up to 20 percent of its gasoline consumption with existing technology.[16]

From the beginning the program was probably not cost-effective, even if all existing sugar industry investment was considered to be a sunk cost. It was limited in that there was no change in the automobile fleet and no expansion of sugar cane production. If sugar and oil prices returned to the historic norms, alcohol production and consumption would be cut back.

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[15] "Wind Power Outlook 2004," American Wind Energy Association, Washington, DC 20001, www.awea.org.

[16] Darius Gaskins, KSG and Bruce Stram, ENRON Corporation, "A Meta Plan: A Policy Response to Global Warming," CSIA Discussion Paper 91-3, Kennedy School of Government, Harvard University, June 1991.

Following the Iranian Revolution and the ensuing run-up of oil prices, the Brazilian alcohol program expanded dramatically. Proponents of alcohol expansion included the Brazilian automobile industry, which had “publicly” committed itself to producing alcohol-only engines, as well as sugar cane producers. Government subsidies were much more extensive, developing autonomous alcohol-only distilleries and the expansion of sugar cane production. The price of alcohol was set well below the price of gasoline. There was an initial boom in alcohol production and the sale of alcohol-burning autos.

By June of 1981, the boom in the sale of alcohol-burning car ceased as oil prices leveled off, sugar prices increased, the government raised the price of alcohol and suspended credits for new distilleries. After a brief pause, the various subsidies were restored in 1982 in the face of rapidly falling oil prices. In 1983, 75 percent of all new autos burned only alcohol and 17 percent of the Brazilian budget was spent on alcohol fuel in one way or the other. Brazil's commitment to alcohol continued, in spite of the continuing decline of oil prices through the 1980's.

By the end of 1989, the alcohol program had created a massive economic crisis in Brazil. The subsidized price of alcohol fuel, which cost the economy approximately $2.5 billion annually, had created a fleet of 4.5 million autos burning only pure alcohol. The government, responding to its soaring international debt, cut subsidies to sugar-cane producers but maintained alcohol fuel prices at 65 percent of gasoline prices in the late 1980's. Farmers shifted into other crops from sugar cane and recently diverted a larger portion of their cane output to produce sugar for export as world sugar prices rose. The bizarre consequence of these policies was a growing shortage of alcohol fuel. Brazil exported gasoline and the government tried to find imported alcohol substitutes, while consumers scrambled to convert their auto engines to burn gasoline.

6. Ozone, CFCs and the Montreal Protocol (Success)

Gus Speth, in his recent book, *Red Sky at Morning*, traces the ozone-layer protection process through its various stages. In terms of outlining the stages in the life of an international environmental regime, he breaks the process down into four stages, as outlined below.[17] In summary, this is a story, in part, of how advancing science can clarifies risks and benefits of various courses of action, or inaction, and when combined with progress in technology that provides a sensible, affordable means for action, real solutions are enabled. Once these two converge, there is a strong basis for broadened consensus, if supported by continued leadership by governments.

The first stage precedes actual international negotiations. It is the stage of problem identification, fact finding, and agenda setting. In many cases, scientists bring the issue forward to the attention of the public and policymakers. In the case of ozone depletion, in 1974, Molina and Rowland published their research showing that CFCs, though highly stable compounds in the troposphere, could release chlorine in the hostile environment of the stratosphere. The chlorine would in turn set off a chain reaction that would deplete the ozone there. CFCs and similar chemicals were in widespread use at the same time. The media, environmental groups, and other raised the issue's visibility. In 1977, the United States, Canada, and Nordic countries called upon the United Nations Environmental Program to undertake a major fact-finding and issue definition exercise. Between 1974 and 1977, the ozone depletion issue moved beyond a question of science and made it onto the intergovernmental agenda.

The second stage is a process of negotiation, bargaining, and agreement on what actions to take. The typical framework convention provides only general findings and policies, statements of broad goals, and institutional and governance arrangements. The more difficult negotiations are reserved for the more specific and action-oriented protocols that follow. In the case of ozone depletion, there was much uncertainty about the seriousness of the problem. In 1984 and 1985, NASA coordinated a major international scientific review, and powerful case for international action was made. The study pointed out that CFCs is the atmosphere had doubled between 1975 and 1985, and it projected a 9 percent depletion of stratospheric ozone by 2150 if 1980 use rates of CFCs continued. Additional skin cancers were estimated. The framework convention on protecting the ozone layer followed promptly in 1985.

Moving beyond the framework convention, the real action in the second stage began in the effort to agree on what became known as the 1987 Montreal Protocol. Before the beginnings of the Montreal Protocol negotiations in 1986, constraining

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[17] Gus Speth, *Red Sky at Morning*, Yale University Press, 2004. Virtually all of this section is quoted directly, or paraphrased, from Speth's account of international policy development on this issue.

measures were resisted by the chemical manufacturers, represented in the United States by the fifty-member Alliance for a Responsible CFC Policy, and by European governments, which at that time tended to adopt the position advocated by their national companies.

But all this was about to change and it is useful to understand why. The industry coalition began to collapse when the single biggest manufacturer, DuPont, announced in 1986 that it could develop CFC substitutes within five years. Also, a major "focusing event" occurred when the ozone hole was discovered over Antarctica. Finally the United States and other governments showed a willingness to compromise. In the end the Montreal Protocol required that the industrial countries reduce their CFC production by 50 percent below 1986 levels by 1999.

The third stage in the treaty-making process is the formal adoption stage. Conventions and protocols are first signed, but do not "enter into force" until they are ratified by a specified number of countries or, its solution.

The final stage of the convention/protocol process is that of implementation, monitoring, assessment, and strengthening. Here again, the ozone convention process is instructive. Driven by further science and by "focusing events" like the ozone hole over Antarctica, the Ozone Layer Conference of the Parties responded repeatedly to strengthen the regime. It also acted to create the so-called Multilateral Fund to support the ability of developing countries to shift to safe substitutes. As political scientist Gareth Porter and his colleagues note, "The Montreal Protocol is the best example so far of a regime that has been continually strengthened in response to new scientific evidence and technological innovations." As a result, if developing nations reduce their emissions as expected, scientists are now forecasting the recovery of the ozone layer by 2050. The Montreal Protocol is a crowning achievement in global environmental governance. Diplomats, corporations, scientists, and environmental leaders succeeded in sharply reducing the release of ozone depleting substances to the point that it is possible to envision recovery of the earth's ozone shield.

7. IGCC Demonstrations (Success)

The development of an integrated coal gasification combined-cycle (IGCC) system has been an important component of DOE's FE RD&D program for more than

20 years. Electricity production from IGCC development was a natural outgrowth of DOE-industry gasification and turbine RD&D that began in the 1970s with the national concern for energy supply alternatives. The perceived goals of the IGCC program include the following: (1) provide a high-efficiency, environmentally benign option for electricity production to ensure the viable use of coal and residual petroleum carbon as a stable energy source, (2) enhance U.S. national manufacturing competitiveness for electricity generation systems, and (3) develop the potential for integrating energy production with commercially useful chemical by-products, including liquid fuel production.[18]

The IGCC technology integrates the advances in high-pressure gasifiers with a combination of advanced gas turbine designs and conventional steam turbines to produce electricity at thermal efficiencies at least 10 percent greater than conventional steam power plants. The fuels that can be used include coal, residual oils and tars, and petroleum coke. Though gasification technology has existed for 200 years, pressurized gasifiers producing (combustible) synthesis gas suitable for use in gas turbine combined-cycle applications were not designed until the late 1960s. Also, gas cleanup technology to minimize pollution emissions, as required by today's environmental regulations, was not effectively coupled with the pressurized gasification process until the mid-1970s.

The key to the success of the IGCC technology is the integration of components into an operating system. It is difficult to trace the influence of DOE's basic and applied research programs on IGCC development, in comparison with the efforts of manufacturing industry, which were built on a long history of petroleum technology and chemical processing matched with gas turbine technology. The electricity supply industry's interest in IGCC was also stimulated mainly by the private sector and its concern over the viability of coal as a fuel. However, both government and the private sector realized in the mid-1980s that coal continued to be the preferred fuel for electricity production but had to be used in the face of very stringent environmental constraints. This realization led to considerable industrial investment in a variety of coal-based power generation technologies.

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[18] National Research Council, *Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000,* Committee on Benefits of DOE R&D on Energy Efficiency and Fossil Energy, Board on Energy and Environmental Systems, Division on Engineering and Physical Sciences, National Academy Press, Washington, D.C., 2001. Virtually all of this section is quoted directly, or paraphrased, from the NRC Report.

The first IGCC demonstration with commercial potential took place during the 1980s without direct DOE sponsorship. The plant involved was the Cool Water facility (see Synfuels case study) in California, a joint effort of Texaco-Southern California Edison (Edison International) -General Electric-Central Research Institute of Electric Power Industry (Japan) -EPRI. This 100-MW plant was operated for several years and laid the groundwork, with the advent of new gas turbines, for scale-up demonstrations at 200- to 250-MW capacity in the 1990s.

The Cool Water experience, combining the Texaco gasification island with advanced gas turbine technology and conventional steam turbines, demonstrated that IGCC could offer efficient coal utilization with minimal environmental impact. With the emergence of new gas turbine technology at the same time (see Advanced Turbine Systems Case Study), the stage was set for DOE to play a critical role in commercial-scale IGCC development through sponsorship of the scale-up demonstration of three IGCC technologies under the CCT program in the 1990s.

As a result of more than 20 years' investment on the part of DOE and industry, modern technology for the gasification of coal and other fossil fuels to produce synthetic natural gas has reached a stage of commercially available technology for applications worldwide. The concept of thermally efficient and environmentally benign electricity production from different kinds of coal using an IGCC system also has been demonstrated at the commercial scale using three different gasification technologies. Thermal efficiencies in excess of 40 percent have been obtained, with the prospect of 50 percent for advanced turbine systems. Emissions of air toxic compounds are minimal, contaminated water discharges are negligible, and solid wastes are produced as vitrified material impervious to leaching in storage. The IGCC plants also afford a significant opportunity for the capture and sequestration of CO_2. Technologies to achieve this goal are being investigated in DOE's program.

IGCC development and demonstration provide a good example of a long-term, sustained cooperative public and private-sector-funded program that has taken important steps to achieving national strategic goals. The benefits of this R&D investment are not yet positive economically, but it does give the United States a practical option for maintaining a coal-based electricity resource while meeting environmental objectives.

The experience gained from IGCC developments indicates that the successful development and demonstration of energy production technologies that require large capital investment are greatly enhanced with public and private partnerships, particularly for accelerating technology development to practice. DOEs' main contribution to IGCC resulted from developing a close working relationship with industry to move the technology through the commercial demonstration stage. This is very critical to commercial acceptance in the electricity production sector, where reliability of technology is a primary consideration. Industry is increasingly averse to using its limited capital funds for pre-commercial demonstrations of new coal-based energy technologies. A degree of risk sharing, with public funds injected at the scale-up demonstration stage, assures that new approaches to energy production will experience a smooth transition from bench-scale to full-scale commercialization.

8. NOx Reduction and the Advanced Turbine System (Success)

For years, gas turbine manufacturers had faced a barrier that, for all practical purposes, capped power generating efficiencies for turbine-based power generating systems. The barrier was heat above 2300 degrees F, where available cooling technologies weren't able to protect the turbine blades and other internal components. Since higher temperatures were the key to higher efficiencies, this constraint effectively limited the generating efficiency at which a turbine power plant could convert fuel into electricity.[19]

The DOE's Fossil Energy took on the challenge of turbine temperatures in 1992, and nine years later, its private sector partners produced “breakthrough” turbine systems that pushed firing temperatures to 2,600 degrees F and permitted combined cycle efficiencies that surpassed the 60 percent mark, setting the current world record for turbine efficiency. Among the innovations that emerged from the Department's Advanced Turbine Systems program were single-crystal turbine blades and thermal barrier coatings that could withstand the high inlet temperatures, along with new firing techniques to stabilize combustion and minimize nitrogen oxide formation.

On February 18, 2000, GE Power Systems unveiled the “H System Turbine”, the first gas turbine slated for the U.S. market that would break through the temperature barrier and push efficiencies to unprecedented levels. Using an innovative dry low-

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[19] *DOE Office of Fossil Energy: Technology Successes*, October 21, 2004. Also available at Internet website: http://www.fossil.energy.gov/programs/powersystems/turbines/turbines_successes.html.

NOx combustion system, the turbine achieved nitrogen oxide emission levels of nine parts-per-million, half the average of the turbines in commercial use. A 50-hertz version, specially designed for the European power grid, was shipped to Baglan Bay Power Station near Cardiff, South Wales, in December 2000 and began test operations in November 2002.

In May 2001, the Energy Department's other advanced turbine development partner, Siemens Westinghouse, announced that its advanced W501G turbine had gone into commercial operation at the 360-megawatt, combined cycle Millennium power plant in Charlton, Massachusetts. In addition, the City of Lakeland, Florida's McIntosh Unit 5, a 249-megawatt simple cycle plant, also went into operation using the advanced turbine at about the same time. The Siemens Westinghouse engine demonstrated a net efficiency of approximately 58 percent in combined cycle application.

In these two cases, the role of the Federal government was to provide visionary leadership on high-efficiency, low NOx technology. The terms of the public-private partnership are illuminating. Over an eight-year period, with a total public-private investment of nearly $1 billion, the government agreed to front most of the costs of the highest risk research in the early years. Based on negotiated milestones and performance measures, if met, private sector investment would then follow and continue the technology to the commercial stage. Carefully tailored and well-managed program, in close partnership with business, resulted in new technology thought “not-possible” just years earlier.

9. Breeder Reactor Demonstration (Failure)

The Clinch River Breeder Reactor Program was authorized by Congress in 1970 and initial appropriations were provided in 1972. The idea was to build a reactor that would produce (breed) its own fuel, a technology that might prove cost effective in a world of increasing electricity demand and rising uranium prices. However, even when the Atomic Energy Commission initiated the project, its own cost/benefit studies were unfavorable and the capital costs of developing the breeder reactor escalated over time.

The cost of the project was estimated in 1972 to be $699 million, based on conceptual designs. In 1973, utilities committed themselves to pay $257 million, plus interest, to the CRBRP. The Department of Energy estimated that interest would raise the utility commitment to more than $340 million. After detailed cost estimates and reference designs were completed in 1974, the estimated costs of the project rose to over $1.7 billion, assuming operation in 1982. Funding restrictions, delays, licensing requirements, and cost re-estimates further raised the estimated costs to over $4 billion. In the Continuing Appropriations Act for Fiscal Year1983, the Congress directed the Department of Energy to report on options to secure additional private sector participation in the CRBRP that would reduce the federal budget requirements. An initial report was submitted in March, and a second more detailed plan was submitted in early August. No funds were included in the Energy and Water Appropriations Act of 1984 and the project was terminated in 1985.[20]

Meanwhile, what falling oil prices did to synthetic fuels programs, falling uranium prices steadily undercut the justification for uranium extension. The economics of the breeder reactor, never that attractive to begin with, quickly became untenable. In 1981, the breeder reactor became one of the few programs that the Energy Research Advisory Board ever recommended terminating. The Senate discontinued funding for the project in 1983.

Although the breeder reactor received some funding from the private sector, it is a clear case of government-industry failure. The project never involved the private sector as a significant and defining partner. It was a technology-push project, without market support. As the project suggests, there can be a tendency for government programs to gain a significant inertia that, if left unchecked, encourages continuation, even when the initial need for those programs disappears.

10. Solar Power Tower Demonstration (Failure)

Demand for Solar Thermal Energy (STE) systems has never materialized in a broad way in the U.S., but there have been two major STE programs. The first was the Solar Power Tower, using a field of reflectors beaming concentrated sunlight light on a central steam-generation tower. The Solar Power Tower was financed as a demonstration by grants from DOE, EPRI, utility companies, and participating

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[20] Congressional Budget Office, Budget Analysis Division and Tax Analysis Division, "Comparative Analysis of Alternative Financing Plans for the Clinch River Breeder Reactor Project," Staff Working Paper, September 20, 1983, http://cbo.gov

equipment vendors. The second was the Solar Electric Generating Station (SEGS) projects developed by Luz, an Israeli company, using parabolic trough reflectors. SEGS was financed on a project-finance basis using a limited partnership structure that flowed the benefits of solar investment tax credits to the investing partners. Both projects created useful knowledge about technology barriers to economic power production from diffused energy source, but neither was sustainable as a continuing venture, even after all capital costs were treated as sunk costs. The solar thermal power demonstrations of the 1970s were among the technology legacies of that era, where idealized concepts were supported politically and subsidized, without a sound business plan for commercialization or partners.[21]

11. High Efficiency Windows (Success)

This is an example of entirely new technology selling itself, with major beneficial impacts on energy efficiency and the environment. The energy equivalent of the Alaskan North Slope's yearly output of oil flows as lost energy through the Nation's windows each year, at a cost to consumers of about $25 billion. The Department of Energy's research efforts to reduce this flow yielded a series of ever-more-efficient windows that, by 1993, had captured 36 percent of the new-window market, a market estimated to have a total annual value of $4 billion in 1995. So-called “low-E,” or “low emissivity” windows are now the primary window technology for new windows, and are estimated to save approximately $7 billion per year in consumer energy costs.[22]

Scientists at one of the Department's national laboratories studied window design and how heat and light passes through windows. They concentrated on low-emissivity coatings that, in cold climates, admit sunlight while blocking heat radiation from within a building. Unfortunately, in the mid-1970's, such coatings were poor quality and too expensive. So the laboratory mounted an R&D campaign, working with industry, to develop prototype coatings using thin-film deposition, while the laboratory itself tested coatings and made computer models to help design coated windows. The results were

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[21] Eckhart, Michael T., Solar International Management, Inc., “Financing Solar Energy in the U.S.” Scoping Paper, August 1, 1999.

[22] *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, U.S. Department of Energy, June 1995.

so promising that by the early 1980's, several large manufacturers had picked up the technology, invested large sums in manufacturing systems, and were marketing their first low-emissivity products. They rapidly progressed to second-generation coatings that were more durable over a wider climate range. By 1987, low-emissivity windows constituted 17 percent of windows sold.

Further research yielded a “super-window” that actually loses less heat than the best insulated walls. It combines multiple coatings and low-conductivity gases within multiple glazing. And for windows in hot, sunny climates, researchers found coatings that can pass light while filtering out solar heat.

CONCLUSIONS

In cases of clear and present danger, where society faces, for example, known effects of toxins, pollutants, or unsafe practices, the policy mechanism of choice, indeed, often of necessity, is regulation. Safety and health standards, guided by science and assessments of risk, are set. Costs of compliance are then determined by markets, with technologies and alternatives vying for the lowest cost means for meeting standards. The resulting benefits to society are internalized in the economic activities associated with the risks. The economics of supply and demand adjust markets efficiently, with minimum distortion. Results are monitored and remedies refined – a tried and true approach to environmental protection.

In the case study about the Earth’s protective layer of stratospheric ozone and its degradation by CFCs, progress toward an appropriate remedy, adopted in 1987 and first effected in 1992, was stymied for more than decade after the mechanism of ozone destruction, itself, was revealed in 1974. The delay was caused, in part, because the risks to society were uncertain at the time, or at least not clearly transparent and, in part, because practical remedies for addressing the problem were not available or too costly.

Advances in related science and technology together helped break the impasse. Atmospheric science created important new knowledge and revealed a growing “hole” in the ozone layer over the Antarctic, clarifying risks. Technology gave rise to practical substitutes for CFCs. Once both developments had emerged, consensus broadened and the coalition of resistance collapsed. The Montreal Protocol was the result, which has since been refined.

Generalizing, in cases where risks exist, but causes are uncertain and the dangers are not widely perceived as clear and present, that is, when dangers to humans are uncertain, diffused, unevenly allocated or distant in time and place, one can expect difficulty in achieving consensus on what, if any, courses of action might be warranted. In such cases, risks and benefits of various courses of action, or inaction, are poorly defined. Also, practical remedies may not exist or are too costly or disruptive. Traditional approaches to environmental protection in such cases may not be able to attract much support. However, investments in science and technology can create new knowledge and bring forth practical alternatives, which might form the basis for future support.

In the meantime, if risks are threatening at some level of probability, and if the consequences are potentially serious, then interim solutions call not for "no action," but for "hedging strategies." These can address the potential of risk, reduce uncertainty, create options for action, and spread costs over all of society through government funding, rather boring in on individual segments of society, which can be expected to resist most strongly if singled out.

The 11 case studies reviewed in this paper constitute various approaches under the overall framework of hedging strategies. They include both "successes" and "failures," viewed from the benefit of hindsight. Collectively, they suggest a number of lessons learned, as follows:

First, government-sponsored RD&D can be a powerful policy tool. When focused on long-term strategic interests, it can envision "stretch" goals, serve important public interests, inspire actions by others, and enable means for goal achievement. When programs are carefully developed, in partnership with private interests and markets, the government leadership can help underwrite risks of early development, attract private interest, where none otherwise might have existed, leverage resources, and spawn new industries, which later may prove to be important elements of longer-term, sustained solutions.

Second, the way in which government goes about stimulating innovation matters. Case studies suggest tailored approaches to technology policy, undertaken with private sector involvement in both research planning and funding, can avoid mistakes of the past. The Brazilian experience with alcohol fuels, the U.S. experiences with synfuels, the breeder reactor, and the Barstow Power tower, should teach lessons of prematurely selecting technology and then making major policy commitments to the "winners." Just as "winners" should not be selected without careful evaluation of all the factors involved (technical requirements, economics/costs, environment, industry needs, etc.), other possible solutions should not be rejected without the same careful evaluation. A portfolio approach to strategic goals would be advised. Relevant industries should be involved early in the process. RD&D planning should include elements at the outset regarding commercialization.

Third, policies intended to promote technology diffusion also need to be carefully tailored to each situation. Some technology is so advantageous in its own right that it sells itself (e.g., advances in oil exploration and development, low-E windows). In other cases, technology is anticipatory in nature and may need a temporary set of "bridge" policies to underwrite costs and incentivize the creation of a new industry. Because technology costs come down through "learning by doing," some government support of industry may be warranted before such technologies can stand on their own. Of the cases studied, the production tax credits (e.g., wind, coal bed methane) seem to have the most direct effects, as were some of the more carefully planned, cost-shared RD&D demonstration projects (e.g., IGCC, advanced gas turbine).

Fourth, in view of some of the cases, caution should be advised when venturing into economic policies under the guise of technology advancement. In some cases, the momentum of special interests carried the technology policy far beyond any of the initial justifications (e.g., alcohol fuels in Brazil). Eventually, these became untenable in the extreme and collapsed.

Finally, as discussed here, hedging strategies are technology policy initiatives that augment RD&D and stimulate new technology adoption, but stop short of regulation and its market-based derivatives. Hedging strategies may be appropriate for a particular point in time, but the cases reviewed here suggest that they are not usually sustained indefinitely. Such strategies often draw their motivations from circumstances that are inherently fluid and dynamic.

At the outset of emerging issues, hedging strategies are attractive in that they address risk under conditions of uncertainty, yet operate at relatively low cost and with minimum economic dislocation. Their presence in the marketplace can infer a value, or shadow price, for a desired policy goal or market behavior. If incentives are in place long-enough and with predictable time periods, businesses can make money promoting technology adoption, while increased production can help establish an infant industry, bring on innovation and lower costs. The successful cases suggest that such initiatives (e.g., the wind and CBM production credits) can have strong effects in accelerating a technology's commercialization, albeit in a selective and potentially distorting way vis a vis other competing technologies.

But such strategies are typically more effective in the early stages of technology evolution. Also, they operate on the margins of the economy and have light overall effect. As strategies that balance in the middle, hedging strategies often eventually tip in one of two ways, depending on how circumstances may change with time. Some tip toward less or phased-out policy frameworks, such as with the synfuels promotions (i.e., the issue was eventually redefined as oil security concerns diminished and high prices fell), or as with the industry-adopted technologies (i.e., technologies matured into market successes), like the low-E windows, ATS, diamond drill bits, and the CBM production credits. Others tip toward broader and more encompassing policy frameworks, such as with the Montreal Protocol, where the underlying issues became better understood, new technologies enabled more practical and less disruptive solutions, and the courses of action became more broadly accepted.

In the meantime, until uncertainty is reduced, remedies are more compelling, and the desired policy courses of action are clear, hedging strategies and related policy frameworks can play important roles in augmenting RD&D and stimulating innovation and technology adoption. They can give rise to new and important technology developments and spawn self-sustaining industries. These, in turn, can bring to commercial reality more practical technology options, which themselves could contribute to broadened consensus, and ultimately make a difference.