Appendix 6

Department of Energy Biological and Environmental Research

The 1973 oil crisis highlighted the need to consolidate U.S. energy policymaking. Six months into his administration, President Jimmy Carter created the Department of Energy (DOE) by combining the Federal Energy Administration, the Energy Research and Development Administration (ERDA), the Federal Power Commission, and several other programs. The roots of the former agencies stretched back to the Manhattan Project of World War II and the postwar years, when agencies were set up to manage the nuclear weapon, naval reactor, and energy development programs (ERDA) and regulate the nuclear power industry (Nuclear Regulatory Commission).

DOE has had a substantial science program since it was created in 1977, courtesy of ERDA and other predecessor agencies. The budget structure of the department is complex, reflecting the various missions of its ancestor organizations. The structure has also evolved as national science priorities have changed. Thus it is difficult to analyze trends in research funding for forest sector energy topics.

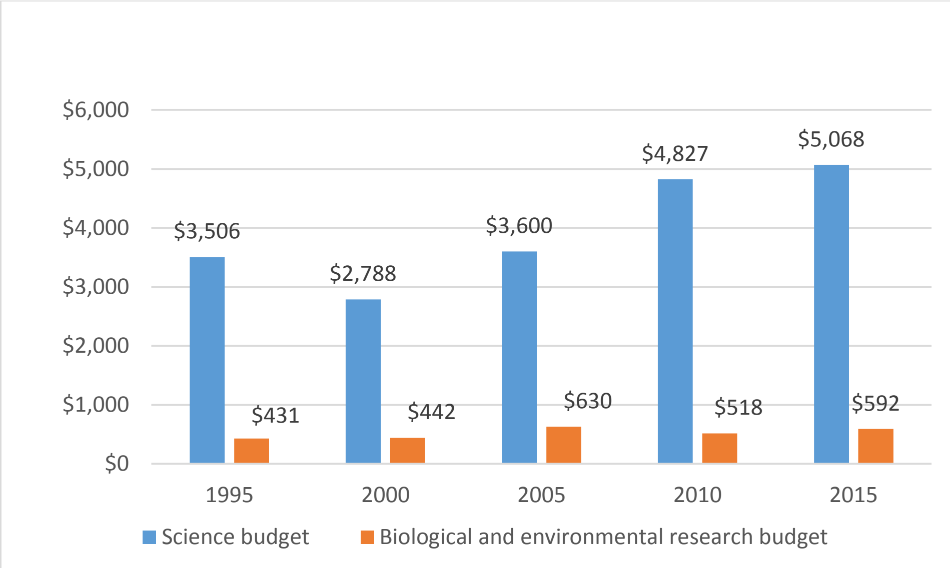

Figure 1. DOE science budget and biological and environmental research funding (million nominal dollars)

The department's Biological and Environmental Research (BER) portfolio contains the research programs of most interest to the forest sector, much of it conducted at the Oak Ridge National Laboratory and the Savannah River site; some forest-related research has also been done at the Argonne and Lawrence Berkeley national laboratories.

The overall science budget of the department has fluctuated over the past two decades, but the percentage of the science budget devoted to BER has consistently hovered around 11–12 percent, except for 2005, when it was 17 percent. A report by the National Research Council (2002) identified three elements of the science program and their funding: terrestrial carbon processes, ecosystems research, and the National Institute for Global Environmental Change, which together received $8.4 million in 1998, $12.8 million in 1999, and $10.7 million in 2000. In fact, however, the budgets of the department (http://www.Science.energy.gov/budget) indicate that global climate change research and other forest-related topics have received considerably more. For example, the explanatory notes for the FY 2000 budget show $119.9 million for global climate change research as part of the U.S. Global Change Research Program and $33 million for a climate change technology initiative.

Budget structure

Until 2010, the Biological and Environmental Research portion of the science budget had four components: Life Sciences, Climate Change, Environmental Remediation, and Medical Applications and Measurements. In 2010, these were reorganized into the following areas:

- *Biological Sciences:* genomics science, radiological science, and biological facilities and infrastructure; and
- *Climate and Environmental Sciences:* atmospheric systems, environmental systems, climate and earth system modeling, and climate and environmental systems infrastructure.

Much of the work in the Climate and Environmental Sciences portfolio dealt with carbon emissions and their effects on terrestrial ecosystems, including carbon sequestration in forests. Further, according to the budget narratives provided for genomics work in the Biological Sciences portfolio, a good deal of funding was allocated to improving the accuracy and efficiency of gene sequencing, using poplar as the initial subject.

Biological Sciences program

The genomic science activity accounts for more than 85 percent of the funding in this category. The major objectives of the genomics research are to determine the molecular mechanisms, regulatory elements, and integrated networks needed to understand genome-scale functional properties of microbes, plants, and communities; develop “-omics” experimental capabilities and enabling technologies needed to achieve a dynamic, system-level understanding of organism and community functions; and develop the knowledge base, computational infrastructure, and modeling capabilities to advance predictive understanding, manipulation and design of biological systems.

A major effort is understanding the biology of plants and microbes as a basis for developing cost-effective ways to produce biofuel from cellulosic (plant fiber–based) biomass. Current research foci include fundamental research on new plant feedstocks for bioenergy, new sustainability research for bioenergy production, biosystems design to develop new plants and microbes with bioenergy potential, and environmental microbiological research to understand the cycling and fate of carbon, nutrients, and contaminants in the environment. These systems biology efforts are supported by the ongoing development of bioinformatics and computational biology capabilities.

Bioenergy research centers

In 2007 as part of the genomics science portfolio, BER established three bioenergy research centers to accelerate breakthroughs in basic science needed to develop cost-effective technologies to scale up commercial production of cellulosic biofuels. The first five-year program of work for the three centers was renewed for a second five-year span in 2012. The centers have been funded consistently at $75 million a year since 2008.

The ultimate goal for the three centers is an advanced cellulosic biofuels industry. Using systems biology approaches, research focuses on reducing production costs. For these biofuels to be adopted on a large scale, they must be environmentally sustainable and economically competitive alternatives to existing fuels. Findings from the centers’ basic research are addressing three challenges:

- developing next-generation bioenergy crops;
- discovering and designing enzymes and microbes with novel biomass-degrading capabilities; and
- developing microbe-mediated strategies for advanced biofuels production.

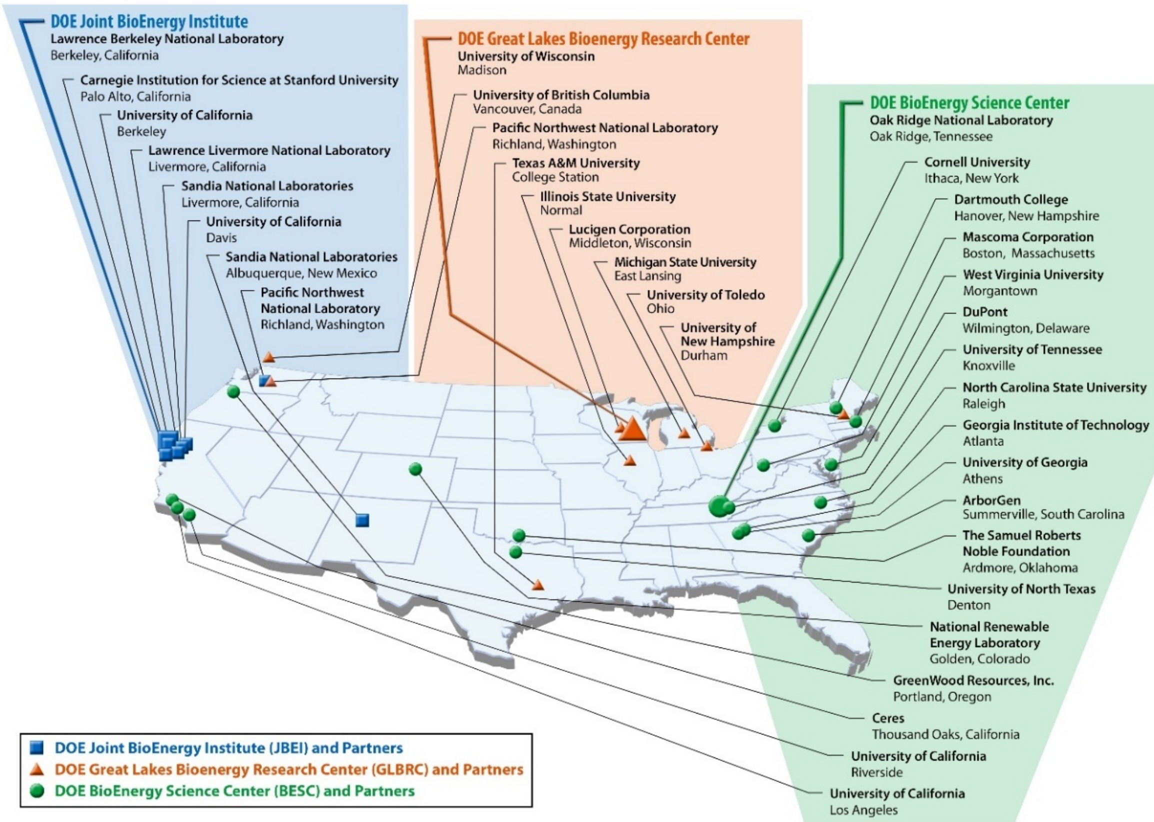

Figure 2. Bioenergy research centers and their partners

Each center is a multidisciplinary, multi-institutional partnership of universities, national laboratories, and the private sector. The centers are supported by multidisciplinary teams of top scientists from universities, national laboratories, nonprofit organizations, and private companies. Each is studying different plants with feedstock potential.

Expertise spans the physical, chemical, biological, and computational sciences, including genomics, microbial and plant biology, analytical chemistry, computational biology and bioinformatics, and engineering. Areas of fundamental research include the identification, characterization, and systems-level regulation of genetic traits for cell wall composition of model plants, such as *Arabidopsis thaliana* and rice, for which detailed genome sequences and phenotypic information are available, as well as second-generation bioenergy crops, such as poplar and switchgrass, for which genomic resources are currently more limited. Other studies focus on understanding the metabolic pathways in individual microbes or microbial consortia that carry out efficient degradation of cell wall material and conversion into ethanol, hydrocarbons, diesel, and even jet fuel. The BRCs are structured to facilitate knowledge sharing among multiple disciplines so that breakthroughs in one area can be capitalized on and translated to other areas of emphasis. In these integrated and collaborative environments, the BRCs pursue the necessary fundamental research to improve the processes needed for large-scale, cost-effective production of advanced biofuels from cellulosic biomass. Additionally, as each center approaches biofuel production challenges from different angles, the types of knowledge gained are multiplied, new questions opened up, and new avenues of research pursued, ultimately accelerating the pathway to improving and scaling up biofuel production processes.

Lignocellulosic biomass research

The Energy Independence and Security Act of 2007 set renewable fuel targets and fostered new research on development of a domestic lignocellulosic-based biofuels industry. Specific and readily achievable targets for ethanol production, first established under the Renewable Fuel Standard as part of the Energy Policy Act of 2005, were revised and updated in the 2007 legislation. These ethanol targets sparked the development of a corn-based ethanol industry that helped drive record U.S. corn production but also presented a conflict between the use of grain for food and for fuel. In the 2006 bioethanol roadmap report, several alternative feedstocks—perennial grasses, woody shrubs, and trees—were identified as potential substitutes for maize grain; what was needed was technology to convert lignocellulosic biomass to sugars and, ultimately, ethanol. Feedstock transportation and densification (e.g., pelletization) processes contribute significantly to biofuel production costs, but the choice of feedstocks depends on regional growing conditions as well as transportation and access to refineries (Figure 3).

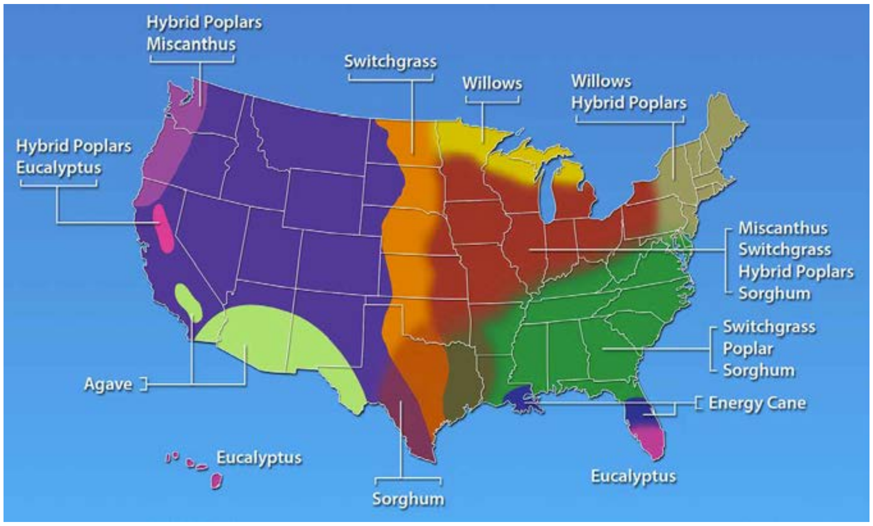

Figure 3. Potential feedstocks for bioenergy production

In 2006, plant biomass recalcitrance was identified as the main barrier to cellulosic ethanol. Progress required understanding the chemical and physical structures of plant cell walls, how they are synthesized, and importantly, how they can be deconstructed. The basic research roadmap that emerged addressed plant biomass recalcitrance but also outlined six basic science goals for bioenergy research:

- sustainable, effective, and economical methods for feedstock production, harvest, deconstruction, and conversion to ethanol;
- creation of a new generation of energy crops with enhanced sustainability, yield, and composition;
- enzymatic breakdown of cellulosic biomass to its component five- and six-carbon sugars and lignin;
- co-fermentation of sugars to ethanol;
- the consolidation and integration of processes to reduce costs, improve efficacy, and reduce generation of and sensitivity to inhibitors; and
- improved overall yields and economic viability in biorefinery environments.

In 2014, to assess the current state of the science regarding lignocellulosic biofuels and identify remaining challenges to a viable biofuels and bioproducts industry, DOE convened a workshop with 45 experts from industry, academia, and DOE national laboratories. Presentations and breakout discussions addressed biomass development, lignocellulose deconstruction, specialty fuels, and bioproduct development from biomass. The workshop report (Figure 4) found that the previous eight years of research had yielded a deeper understanding of plants, particularly cell wall composition and the effects of changing cell wall composition on plant physiology. Additionally, researchers had more insight into the chemical, enzymatic, and microbial deconstruction of plant cell walls, as well as an understanding of how to engineer saccharolytic microbes. Other studies, such as the *U.S. Billion Ton Update* (http://energy.gov/eere/bioenergy/downloads/us-billion-ton-update-biomass-supply-bioenergy-and-bioproducts-industry), have looked at the biomass supply and process development issues needed to support a biofuels industry. These technical insights and scoping data are critical for developing a sustainable biofuels and bioproducts economy.

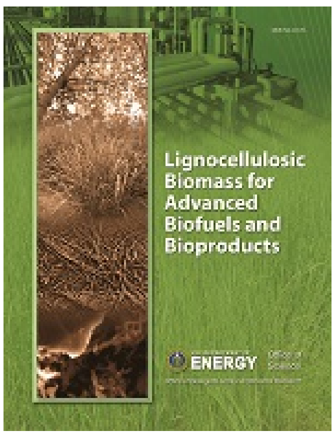

Figure 4. Report of June 2014 workshop (U.S. Department of Energy 2015)

Biomass recalcitrance is still the biggest obstacle to low-cost biomass processing. Recalcitrance directly affects yield, and the basic scientific questions most relevant to the emergence of a cellulosic biofuels industry continue to revolve around increasing the yield of sugars from biomass, the concentration of these sugars in the fermentation medium, and the rate of enzymatic hydrolysis and fermentation processes.

In 2014, a few lignocellulosic biorefineries came online in the United States. These first-generation biorefineries will test economic and agronomic models for an efficient and sustainable lignocellulosic advanced biofuels and bioproducts industry. Additionally, bioenergy research goals are shifting and expanding from the economical production of lignocellulosic ethanol to the economical production of lignocellulosic advanced biofuels and bioproducts. Of particular interest is the potential for aromatic products derived from lignin: they offer an attractive alternative to petroleum-derived aromatic compounds because they use less toxic starting materials and potentially can be tailor-made by plants. The startup of commercial demonstration projects summarized in Table 1 will drive further basic science by identifying unanticipated challenges and help prioritize areas of research—whether at the molecular, systems, or process levels.

Table 1. Commercial-scale bioenergy production, 2015

Firm	*Location*	*Biomass feedstock*	*Product*	Annual output* (million gallons)
Abengoa	Hugoton, KS	Agriculture residues, dedicated energy crops	Ethanol	25
American Process	Alpena, MI	Hardwood, mill waste	Ethanol	1
DuPont	Nevada, IA	Agricultural residues	Ethanol	30
FIerright	Marion, IA	Municipal waste	Ethanol	6
INEOS	Vero Beach, FL	Yard waste, municipal waste	Ethanol	8
POET-DSM	Emmetsburg, IA	Agriculture residues	Ethanol	20

* Volumes as reported by companies

The past decade has also witnessed a tremendous level of private investment in the development of new biofuels processes, addressing not only the barriers to cellulosic ethanol but also “drop-in” biofuels that are compatible with existing engines. One example is the $500 million Energy Biosciences Institute led by BP (formerly British Petroleum) at the University of California–Berkeley and University of Illinois. Established companies (e.g., DuPont, BP, and Monsanto) and private ventures have invested more than $1 billion, resulting in several public offerings (e.g., Amyris, Solazyme, Gevo, and Codexis).

Most of the gasoline now sold in the United States contains some ethanol. Gasoline with 10 percent ethanol content is referred to as E10. Currently, the U.S. market for E10 is saturated with corn and cane ethanol, and the E15 and E85 (gasoline with 15 and 85 percent ethanol content, respectively) markets have been slow to open up, limiting expansion of the bioethanol market. In the absence of policy or market incentives for more bioethanol, the focus shifts to the production of nonethanol biofuels. This also create opportunities for upgrading and converting biologically produced intermediates into finished products as well as hybrid biochemical-chemical processing options. Exploring these opportunities—and in particular, identifying the basic bioenergy science needed—was the primary reason for the 2014 DOE workshop.

Biomass Research and Development Initiative

In the early 2000s, USDA's National Institute of Food and Agriculture (NIFA), the Institute of Bioenergy, Climate, and Environment (IBCE), and DOE's Energy Efficiency and Renewable Energy Field Office, Bioenergy Technologies Office began working together to support the development of a biomass-based industry in the United States. The original legislative authority was provided in section 9008(e) of the Farm Security and Rural Investment Act of 200, as amended (Pub. L. 107-171) (7 U.S.C. 8108). This section called for collaboration between DOE and USDA in creating the Biomass Research and Development Initiative (BRDI). In 2008, section 9001(a) of the Food, Conservation, and Energy Act of 2008 (FCEA) (Pub. L. 110-246) reauthorized BRDI and continued the financial assistance program. Additionally, DOE provides funds guided by certain administrative provisions of the Energy Independence and Security Act of 2007 and the Energy Policy Act of 2005. BRDI's legislative mandate is for research and technology development in three areas: feedstocks development, biofuels and biobased products development, and biofuels development analysis.

Other agencies have since joined the research initiative, but no government-wide summary or "cross-cut" of budgeted amounts or program expenditures on BRDI is available. Within NIFA, $8.7 million in grant funding (20 percent match for research, 50 percent for demonstration projects) was available in 2015 (https://nifa.usda.gov/funding-opportunity/biomass-research-and-development-initiative-brdi. Individual departmental budget explanatory notes regarding BRDI provide the only information. As a result, congressional appropriations subcommittees, whose jurisdictions differ, see an incomplete picture of the interdepartmental program's total funding and emphasis areas.[1] For more information about BRDI, see Appendix 4.

Climate and Environmental Sciences program

Climate and Environmental Sciences, the other major subprogram in BER, supports fundamental climate-relevant atmospheric science and ecosystem process and modeling research. This includes research on clouds, aerosols, and the terrestrial carbon cycle; large-scale climate change and earth systems modeling; the interdependence of climate change and ecosystems; and integrated analysis of climate change effects on energy and related infrastructure. It also supports subsurface biogeochemical research that advances fundamental understanding of coupled physical, chemical, and biological processes controlling both the terrestrial component of the carbon cycle and the environmental fate and transport of energy by-products, including greenhouse gases.

This portfolio of research, extending from the molecular level to field scales, emphasizes the coupling of multidisciplinary experimentation and advanced computer models. It seeks to develop predictive, systems-level understanding of the fundamental science associated with climate change and other energy-related environmental challenges and to build a foundation for developing predictive climate and earth system models, with special focus on areas of critical uncertainty, including Arctic ecology and permafrost thaw, tropical ecological change, and carbon release. It also seeks advances in environmental cleanup and reductions in life-cycle costs.

In Figure 5, the blue bars represent funding most directly related to forestry and forest-sector research—bioenergy and climate change. These areas consistently account for one third of the BER budget over the years presented. The bulk of the funding for Climate & Environmental Facilities & Infrastructure supports two facilities—the Atmospheric Radiation Measurement

[1] Even within a single department, subcommittee jurisdictions vary. For example, the Forest Service and Environmental Protection Agency research programs are within the jurisdiction of the appropriations subcommittees for Interior, Environment and Related Agencies. The remainder of USDA programs are the responsibility of the subcommittee for Agriculture, Rural Development, Food and Drug Administration and Related Agencies. DOE programs are the responsibility of the Energy and Water Development subcommittee.

Laboratory and the Environment Molecular Sciences Laboratory—that are less directly involved in bioenergy and terrestrial ecosystems research.

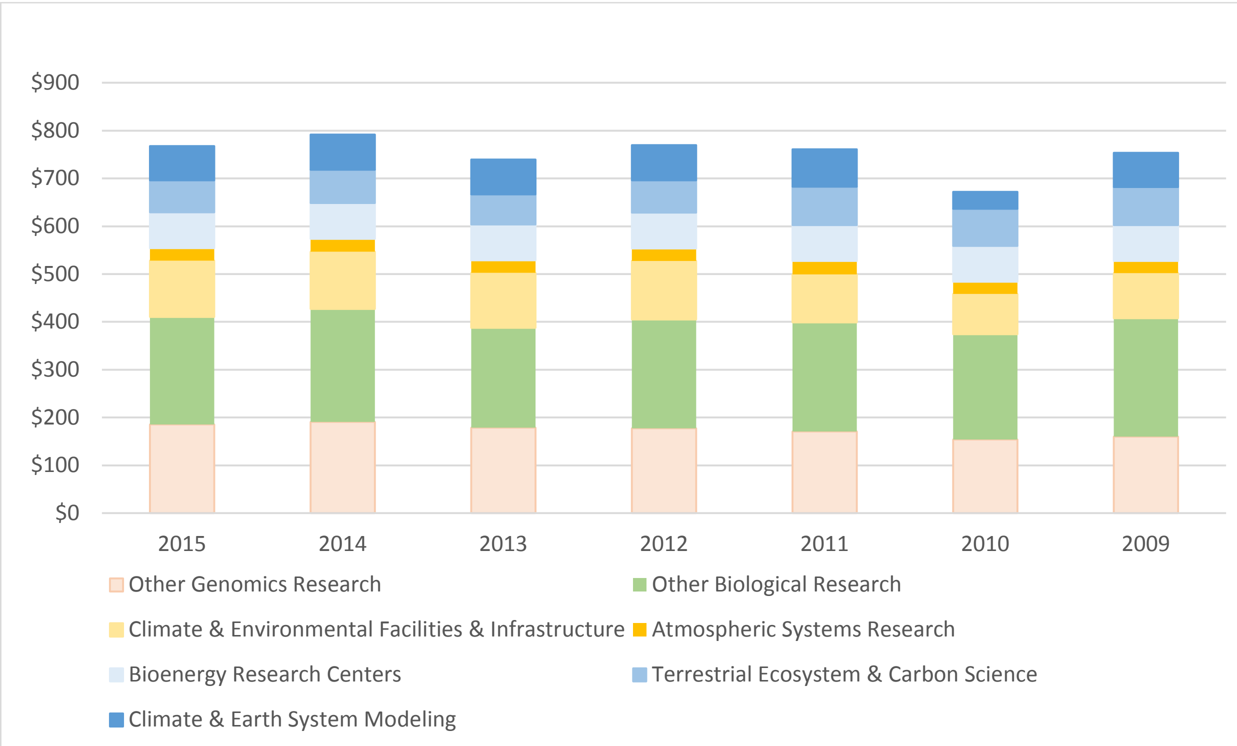

Figure 5. Biological and Environmental Research budget components (million nominal dollars)

Analysis of the data for FY 2000 to FY 2008—difficult because of the budget structure—suggests that biomass emerged as a distinct research focus in 2006–2007. Before then, climate change was a research emphasis, accounting for 22 to 25 percent of the BER budget.

Another recent shift is a reduction in research on radiation's effect on humans. From 2000 to 2006, the emphasis was on the health effects of both low doses, associated with medical scanning equipment, and large doses encountered in accidents. In more recent years, that research emphasis has faded while biomass energy research has ramped up.

Conclusions

Three conclusions can be drawn from this review of the Department of Energy's research. First, the science program leaders were willing to make major shifts in the focus areas over time as science priorities changed. Second, research programs responded to emerging socioeconomic and political concerns, notably fluctuations in world crude oil prices and the effects on the U.S. economy and citizens. Third, program leaders created a major new research initiative, through the bioenergy research centers, that relied heavily on public-private partnerships to accomplish near-term goals.

Regarding the first conclusion, the earlier research emphasis on human exposure to radiation followed the 1979 meltdown of a nuclear reactor at Three Mile Island, Pennsylvania, which was partial and contained, and the 1986 explosion of the Chernobyl power plant in Russia, which caused widespread release of radiation, human deaths, and environmental contamination. But after 20 years of research, it was deemed time to wind down that work.

Regarding the second and third conclusions, fluctuations in the prices for crude oil led to new research initiatives. Fluctuations in the “world price”[2] for crude oil hammered U.S. consumers for a decade (1973 to 1983) after the Organization of Petroleum Exporting Countries imposed an embargo in response to the Yom Kippur War of October 1973. Prices then dropped for two decades, but by 2005 they were climbing again, raising questions about energy security and the potential for alternative fuels. Legislators responded by funding the bioenergy research centers and the Biomass Research and Development Initiative. The result was a major increase in funding for DOE and several other agencies, including NIFA.

Two leadership emphases were vital: creating an aggressive strategic plan with clear research objectives, and creating new research centers that were public-private partnerships involving DOE (and several other federal agencies, including USDA) and a wide assortment of industry, university, and other private research partners. Although some brick-and-mortar capacity building was part of setting up the three research centers, the “virtual” aspects of the program—bringing partners into the mix wherever they were located—was also important.

The DOE budget emphases have shifted in response to nuclear accidents, oil shortages, and oil price increases. Similar cataclysmic developments have not stirred the forest sector, but the lesson that can be drawn from the DOE experience is that leadership responses are critical.

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[2] The only very long term price series is the U.S. average wellhead or first purchase price of crude. Recall that the United States imposed price controls on domestic production from late 1973 to January 1981. To present a consistent series and also reflect the difference between international prices and U.S. prices, a world price series was created. It adjusts the wellhead price by adding the difference between the refiners’ acquisition price of imported crude and the refiners’ average acquisition price of domestic crude (http://www.wtrg.com/prices.htm).

Science leaders seized the initiative by devising innovative, strategic plans for biomass research with clear, far-reaching goals, and then established three new centers on a public-private partnership model, with total funding of $75 million annually. The leaders chose to manage major shifts in science programs through partnerships rather than doing the bulk of the research in-house.

In future forest sector research initiatives, these lessons might well be applied. Strong leadership in innovative research and development strategies that set ambitious goals, coupled with strong management of a large number of public-private partnerships, might work as well in the forest sector as it seems to have worked in the energy sector.

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