New Benefit-Cost Studies of Renewable and Energy Efficiency Programs of the U.S. Department of Energy: Methodology and Findings

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Abstract

Taxpayers reasonably ask the question "*Energy Research at DOE: Was It Worth It?*" This paper presents the findings of retrospective benefit-cost studies of four programs at the U.S. Department of Energy (DOE), the first such studies since the 2001 National Research Council study with the above title. The research and technology development programs evaluated are Wind Energy, Solar Photovoltaic Energy, Geothermal Energy, and Vehicle Technologies Combustion Research. The methodology used in these studies assesses economic benefits, as well as environmental, security, and knowledge benefits. Economic benefits include energy, labor, and other resource savings. Health benefits from avoided air emissions are expressed as reduced mortality risk and changes in health impacts, and also the resulting change in health care costs are expressed in dollars. The approach uses a technology cluster approach to address an entire program or large part of a major program to provide a lower-bound estimate of the return on the entire public investment. The approach is best practice in the detailed, case-by-case attention paid to selection of the next best alternative for calculation of benefits, and the careful attribution of returns to the public investment. Fundamentals of the methodology are described, accompanied by examples from the four studies. Conclusions include lessons learned from the four studies that will improve the methodology guidelines for future retrospective benefit-cost studies.

Introduction

The United States Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) manages America's investment in research, development and deployment (RD&D) in efficient and clean energy technologies. Through a diverse applied science portfolio, EERE works to change the national landscape of energy supply and demand by developing new renewable energy and energy efficiency technologies and increasing the rate and scale at which these technologies are commercialized. In Fiscal Year 2009 the EERE budget was about 2.2 billion dollars.

EERE is organized around 10 energy programs, shown in Figure 1. Two of these focus on deployment-only: the Federal Energy Management Program and the Weatherization and Intergovernmental Program. Five are RD&D programs in renewable energy technologies: Biomass; Hydrogen and Fuel Cells; Geothermal; Solar Energy; and Wind and Hydropower. Three programs are focused on efficient energy use: Building Technologies; Industrial Technologies; and Vehicle Technologies. The EERE Office of Planning, Budget, and Analysis (PBA) takes an active role in measuring and monitoring the performance and conducting evaluations of EERE's major programs. The focus of these activities is primarily retrospective — that is, they look back to assess whether planned technical goals were realized, and commercialization and market results achieved. The evaluation function does not forecast future benefits. For more information and to access evaluation guides see http://www1.eere.energy.gov/ba/pba/performance_evaluation.html.

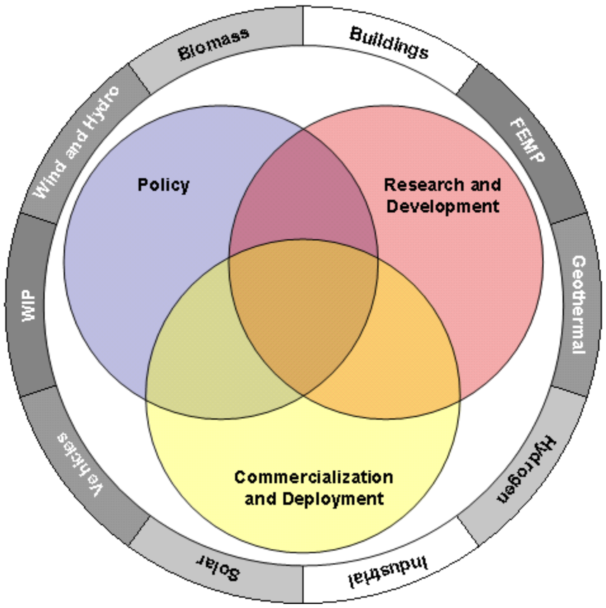

Figure 1. The U.S. DOE Office of Energy Efficiency and Renewable Energy

A New Approach to Benefit-Cost Evaluation

While DOE's research and development (R&D) programs in energy efficiency and renewable energy (EERE) have achieved many technical successes that have resulted in commercialized technologies and products found in today's markets, most of these programs had not yet had independent assessments of returns on their R&D investments as of 2009. The last economic assessment of multiple EERE programs was a 2001 NRC study (NRC 2001). At the same time, it was recognized by DOE program managers that a major Federal energy program that has demonstrated benefits determined through systematic, retrospective evaluation is better positioned to communicate its value to Congress, stakeholders and the public, than one which has not, and, further, that feedback from evaluation is important for improved program design and operation.

In 2009, EERE Office of Planning, Budget, and Analysis along with technology program managers, set about to improve and extend the NRC evaluation approach based on recommendations made by reviews of the NRC study, and to apply it to a selection of EERE programs and subprograms. Goals were to develop a consistent, modified NRC approach for determining realized economic and other net benefits that would: (1) model government additionality (contribution) in detail, on a case-by-case basis, (2) refine and expand environmental benefits, particularly health benefits from reduced air pollution, (3) estimate security benefits as feasible, (4) expand the treatment of knowledge benefits, and (5) calculate returns to a whole EERE program or subprogram, rather than to single projects.

To meet these goals, a new approach was developed, a draft "how-to" Guide (Ruegg and Jordan, 2009) was prepared to implement the approach, and this was reviewed by experts. Experienced evaluators were identified, and four initial benefit-cost cluster studies were commissioned for completion early in 2010. Following completion of the studies, a lessons-learned seminar is scheduled and the experience from these studies will be incorporated into a final version of the Guide. An earlier paper Ruegg and Jordan 2010) captures the basics of the methodology. This paper updates that earlier paper and demonstrates the methodology by reporting findings from the recently completed benefit-cost studies of four EERE programs (Gallaher, Rogozhin and Petrusa 2010; Link 2010; O'Connor, Loomis and Braun 2010; Pelsoci 2010.

These programs, study authors, and technologies assessed in the four studies are shown in Table 1.

Table 1. Four Initial Benefit-cost Studies Using New Draft EERE Methodology

Program/Cluster evaluated	Authors	Technologies assessed in detail	Period studied
EERE Vehicle Technologies Program Cluster: Advanced Combustion Engine Technologies	A. Link University of North Carolina at Greensboro	-Laser and optical diagnostic technologies and combustion modeling related to heavy-duty diesel engines	1986-2007
EERE Geothermal Program Cluster: Program-wide representation	M. Gallaher A. Rogozhin J. Petrusa RTI International	-Polycrystalline diamond compact (PDC) drill bits -Binary cycle power plant technology -TOUGH series of reservoir models -High-temperature geothermal well cements	1976 to 2008
EERE Solar Energy Technologies Program Cluster: Solar Photovoltaics (PV)	A. O'Connor R. Loomis F. Braun RTI International	-Crystalline silicon PV module technologies -Thin Film PV module technologies - Manufacturing technologies -Technology infrastructure for measurement, characterization, and reliability	1975–2008
Wind Energy Program Cluster: Infrastructure Technologies	T. Pelsoci Delta Research Co.	-Turbulence models -Wind tunnel experiments of turbine aerodynamics - Blade materials characterization -Airfoil design codes -Demonstration and testing	1976 to 2008

The evaluation framework

Four categories of net benefits

The evaluation framework used for the new EERE benefit-cost studies allows for a more comprehensive treatment than traditionally provided by benefit-cost assessments focused only on economic benefits. As illustrated by Table 2, there are four categories of benefits and costs included, rather than a focus only on energy savings and other related savings and costs. In row one are the traditionally captured direct impacts on energy, labor, and other resources. In row two are the environmental benefits, including physical units of green house gases and other air emissions, and changes in mortality and morbidity rates from reduced air emissions. A monetary estimate of health effects from reduced air emissions is also included in environmental benefits. The third row, net security benefits, at this time is expressed as equivalent barrels of imported oil avoided, and a qualitative assessment is given of any notable changes in the security of energy system infrastructure. The fourth row, knowledge benefits, includes quantitative and qualitative measures indicating knowledge creation and dissemination derived from patent and publication bibliometric techniques. An example of study results for the four categories of net benefits are presented later in the paper.

Table 2: Categories of Benefits, Costs, and Related Metrics

Category of benefit & cost	**Measurement of realized (retrospective) net benefits and costs**
Economic	Monetary measures of changes in energy, labor, and other resources & qualitative assessment of these effects not valued monetarily
Environmental	Physical units of greenhouse gases & of other air emissions and pollutants; changes in incidence rates of mortality and morbidity & monetary valuation of these health effects (Note: The latter are combined with economic effects in row 1 to provide a broader measure of monetary effects)
Security	Equivalent barrels of displaced imported oil & qualitative treatment of perceived changes in risks to the energy system infrastructure
Knowledge	Quantitative and qualitative bibliometric measures

Economic performance measures, including Net Present Value, Benefit-to-Cost Ratios, and Internal Rate of Return, are provided based on the economic benefits category, and also based on the combination of the economic benefits category and a portion of the environmental benefits category--namely the monetized value of health benefits from reductions in air emissions. For the 2009 studies, this is the only combined presentation of benefits estimated in dollars that is provided, due to greater uncertainty in attempting to assign dollar values to the other categories of benefits. Future benefit-cost studies may be extended to include dollar estimates of other categories of net benefits. It should also be noted that the methodology does not support an examination of cost-effectiveness across technologies or programs.

Technology Cluster approach

The cluster approach compares benefits of selected elements of a defined technology area (see Table 1) to investment costs of the entire associated program or sub-program. The purpose of the cluster approach is to provide an estimate of the lower-bound return for the whole program or sub-program, without performing detailed analysis of all of its funded research projects or technologies. The approach works well for high-risk R&D programs where a few projects tend to be the big winners and investment in an array of projects is necessary to find the successful ones. It is a potentially cost-effective approach to demonstrate that benefits from only a few elements in a cluster may more than offset total program/subprogram investment costs.

The retrospective cluster approach begins with identifying a cluster of evaluative interest (i.e., a program or sub-program or other portfolio of projects). Next, a few technologies/projects within the cluster are identified that appear to be among the more successful technically and commercially, and these are selected for detailed benefit-cost analyses. Those not selected for detailed treatment are treated qualitatively, including negative effects, if any. Finally, combined benefits of the technologies evaluated in detail are compared against entire program or sub-program cost, and the results are conditioned by the qualitative results.

Estimating economic benefits and costs

A theoretical anchor for estimating returns

Earlier work by economists Zvi Griliches and Edwin Mansfield (Mansfield 1977, 1996) provided a unifying framework across the studies for valuing social economic returns from investment in new technology. The approach followed takes into account market spillover effects that occur as others in the same industry as the innovator, within competitive markets, use the innovator's knowledge to imitate the innovation and drive down prices to consumers. Included are the effects on customers of the investing/innovating firm and the final consumers of related products and services within the industry.

Comparing new technology in the cluster against the next best alternative

The merits of a new technology are judged against the next best alternative, i.e., the best choice that would be made in lieu of choosing the new technology. For a retrospective benefit-cost analysis, the next best alternative is determined by looking back to the time when the investment decision was made. There are several factors that affect the selection of the next best alternative that may help to inform the selection across studies in a consistent manner. One of these factors is whether the investment decision was constrained or unconstrained, that is, whether the choice was restricted, such as by regulatory requirements, or completely open. Another factor is whether the technology is new to the world or an improvement over an existing system. Another is whether or not dynamic modeling is needed because the alterative technology changed over time in response to the introduction of the technology being studied. The Guide provides an aid for defining the next best alternative for comparison. Choices of next best alternatives in the four recent studies are shown in Table 3, column 2.

Determining program additionality for each technology

A keenly important aspect of estimating the return on EERE's investment, i.e., the "return on public investment," is to provide evidence-based analysis of additionality, that is, the effect the EERE program had on the outcome. This entails delineating the part of benefits from the cluster technologies that is attributable to the cluster costs, and documenting evidence of cause and effect. The public program in question, for instance, may have accelerated technology entry into the marketplace; improved the performance characteristics of the technology; changed the technology's cost; increased market size; it may have had other or no effects. Potential rival explanations of the estimated benefits must be addressed, such that it is the program's effect that is identified in the additionality assessment and not other causes. Eliminating rival explanations is important; otherwise the benefits claimed for the Program could be due to other factors. For example tax credits may constitute a rival explanation for market expansion of a renewable energy that appears attributed to improved system performance resulting from R&D related technology advances. Brief summaries of DOE's effects and attribution for each of the four studies are given in Table 3, column 3; the studies provide in-depth assessments.

The Guide provides an aid for organizing the additionality analysis and for mapping attribution to a technology timeline to show when and how an identified effect is estimated to have occurred. Table 4 is an example of this matrix used for the polycrystalline diamond compact (PDC) drill bit case. The table shows, for example, that DOE played a very important role in developing and adopting the PDC drill bit technology, making significant contribution to (1) developing the bit and getting it to the market, (2) overcoming performance flaws and limitations, and (3) spurring the innovation that resulted in the overall market success of PDC drill bits. This approach to organizing additionality analysis could be applied to any technology development effort. The columns are the linear model of R&D from preliminary research to deployment of a technology. The rows are standard evaluation questions. Who did what, when, and what are rival explanations for taking credit? The columns of the table may need to be modified to more easily incorporate infratechnologies, and attention will be given to possible modification in the forthcoming revision of the Guide.

Computing measures of economic performance

Economic benefits are increases in the value of goods and services in the economy. Technological advancement is one way to increase economic benefits. This occurs by improving the performance of existing goods and services and/or reducing their costs, and by developing novel goods and services that provide desired new capabilities and experiences with economic value. The EERE R&D program may have had any of a number of effects on outcome, including, but not necessarily limited to, the following:

- The Program may have accelerated technology entry into the marketplace such as
  - by speeding the R&D effort which is carried forward into other stages,
  - by increasing probability of technical success,
  - by attracting additional funding for development and commercialization, and
  - by increasing market awareness;
- It may have improved the performance characteristics of the technology such as
  - by broadening the scope of the R&D effort, and/or
  - by increasing the scale of the R&D effort to take on more technical challenges;
- It may have changed the cost of a technology such as
  - by encouraging collaborative R&D activities among organizations to avoid investment redundancy, and
  - by providing specialized facilities and services needed by an entire industry in order to make advances;
- It may have increased market size, such as
  - by reducing barriers to market adoption through information, training, and standards and certification activities, and
  - by increasing access of U.S. firms to growing global markets.

Selected economic performance measures—Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Internal Rate of Return (IRR)—are used to provide estimates of the public return attributable to the EERE program or sub-program. A positive NPV, a BCR greater than one, and an IRR greater than the discount rate each means that benefits to the nation attributed to the EERE program exceed EERE's program/sub-program investment cost. Results are computed for two discount rates (3% and 7%), both defined in accordance with Federal guidance as real rates, exclusive of inflation (OMB, 1992 and 2003). Accordingly, all cost and benefit amounts are expressed in the same year dollars prior to discounting--in these four cases, in 2008 dollars. Sensitivity analysis is performed for other key variables.

DOE Advanced combustion engine R&D had its major benefits from improved control of the combustion process in heavy-duty diesel truck engines, resulting in an estimated savings of 17.6 billion gallons of diesel fuel from 1995 through 2007. DOE Geothermal Technology R&D realized the major part of its benefits from development of PDC drill bits, as well as from binary cycle geothermal plant technology, reservoir computer modeling, and new cements for geothermal wells. DOE Solar

Table 3. The Next Best Alternative, DOE Effect, and Attribution Examined in Four Studies

Study (1)	Next Best Alternative (2)	DOE Effect and Attribution (3)
Advanced Combustion Engine R&D	The state-of-the-art in diesel engine design and related brake thermal efficiency (BTE) that existed prior to 1995.	Brake thermal efficiency (BTE) would have been 4.5% lower than it was actually each year from 1995 - 2007. Benefits are 100% attributable to DOE ACE R&D. The U.S. diesel engine industry would not have been able to conduct the necessary research, even with assistance of universities, based on interviews, studies, and economic theory.
Geothermal R&D (4 cases)		
Polycrystalline diamond compact (PDC) drill bits	Existing roller bit technology.	New technology increased both productivity (feet drilled per hour) and efficiency (number of drill bits per hour). 50% of the economic benefits from PDC bits are attributable to DOE, based on the observable technology transfer, findings from published papers, and interviews.
Binary cycle power plant technology	For reservoir temperatures in the range of 150 to 190^{o}C, flash cycle technology; and for temperatures in the range below 150^{o}C, a coal power plant.	New technology accelerated the entry of the technology to the market by 2 years. The main DOE impact was demonstration of commercial applicability and provision of guaranteed loans which helped industry to obtain financing.
TOUGH series of reservoir models.	"Lumped parameter" models used before capabilities for detailed computer simulation of reservoirs were developed.	Reduced drilling costs and decreased uncertainty associated with well management. DOE had overwhelming influence (80%) on the TOUGH series models, were Influential (20%) on other reservoir models.
High-temperature geothermal well cements	Existing (Portland) cements.	Averaging estimated influence factors over each stage in the technology development cycle yields an estimated 48% attribution rate.
Solar Photovoltaics c-Si modules and thin-films modules	Existing inferior crystalline silicon photovoltaic modules that would have been produced during the delayed introduction of the improved thin film PV modules technology.	12 year acceleration effect on cost reductions and reliability improvements in PV modules. Companies' rates of progress, as measured by year-on-year production cost reductions and reliability gains, would have been lower without DOE R&D.
Wind Infrastructure Technologies	Smaller, less reliable, less cost-competitive wind turbines with reduced energy capture that would have been used during the delayed introduction of the improved infrastructure technologies.	An average of six years delay in technical advances and corresponding wind energy generation levels were avoided with DOE investments in the selected technologies. Accounting for cost share, the DOE attribution rate is estimated at 80% .

Table 4. An Example of a Matrix to Assess Attribution

A Matrix Assessing DOE Attribution of PDC Drill Bit Technology by Stage

Categories of Informat o Needed Additionality Assessmen	Preliminary & Detaile Investigation	Develo Component	Develop System	Validate Demonstrat	Commercializ	Market Adoption
What DOE support of SNL and others did	▪ Study applicability of PRC drill bits geother al	▪ Worked on improvin performance of drill ▪ Finance contracts and R&D efforts with GE	▪ Conducted research on drill mechanics and hydraulic ▪ Develope STRATAPAX PDCWEAR, which helped place cutters on drill	▪ Sponsored we ar friction ▪ Helped establish best practice ▪ Held sponsore publications and presentations	▪ DOE efforts helped commercialize bit	▪ DOE scientists engineers contracted consortium manufacturers to con inue improving the performance of PDC drill bits
What others did (rival explanations)	▪ GE developed in 1955 and first tested in the field 197	▪ GE worked DOE	▪ GE used to position cutters on drill ▪ Industry used PDCW EAR to antiwhir bit			
Driving/ restraining policies/ government forces (rival explanations)	▪ USGS study showed availability U.S. ge .field ▪ Oil crisis, U.S. government studie alternative fossil	▪ Oil crisis, U.S. governmen studied alternative energy sources to fossil (includin geothermal)			▪ Demand for oil went up, creating a demand for offshore drilling	▪ PDC fo horizontal drilling widel used offshore drilling ▪ Federal and State Tax Credits
Description of DOE influence	▪ Very Important (50% ▪ DOE forts helped conside applications of costly PDC drill technology	▪ Very Important (50% ▪ DOE supported the technology at the time when seemed too costly and unreliable	▪ Dominant ▪ Developed analytical tools that helped advance the appli cation of the technology ▪ Greatl improv d bonding of cutters to drill bi	▪ Dominant ▪ DOE efforts helped show that it is possible to overcome the short - comings of PDC drill technology with engineering and research	▪ Influential (5%) ▪ DOE 's helped deliver PDC bits right before a increase demand for a similar technology	▪ Influential (25% ▪ DOE 's remained available for the industry to use in their own R&D fort
Basis evidence for influenc	▪ Interviews expert ▪ Article ▪ Studie	▪ Interviews with expert ▪ Articles ▪ Studie	▪ Interviews with experts ▪ Article ▪ Studie	▪ Interviews with experts ▪ Article ▪ Studie	▪ Interviews wit experts ▪ Article ▪ Studies	▪ Interviews with expert ▪ Articles ▪ Studie
The DOE effect	▪ Accelerate technology entry	▪ Improve performanc	▪ Improved performance ▪ Changed costs	▪ Improved performance		▪ Improve performanc

Photovoltaics R&D between 1975 and 2008 hastened the development and market introduction of higher quality, longer lived, and lower cost PV modules initially by transferring space-based PV expertise to the nascent terrestrial PV industry, and then by refining existing technologies and developing new technologies using novel materials, designs, and manufacturing techniques. DOE Wind Energy R&D yielded important infrastructure technologies that accelerated efficient wind energy generation and resulted in energy and health care cost savings.

Discounted at 7%, the lower-bound estimates of NPV from DOE's R&D in these four programs/sub-programs ranged from a low of just over $1 billion to a high of more than $23 billion, taking into account cost savings from energy, labor, and other resource savings associated with reduced fuel consumption, as well as reductions in health related costs from reduced air emissions. Benefit-to-cost ratios, using a 7% discount rate, ranged from 2.8:1 to 53 to 1.

Estimating environmental benefits and costs

The quantitative estimation of environmental benefits in the EERE benefit-cost studies focused on estimating Green House Gas (GHG) effects, an important goal for EERE, with attention to carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The 2009 draft study Guide recommends the use of the EPA Greenhouse Gas Equivalencies Calculator (EPA 2009) to assist in assessing the consequences of the GHG effects.

GHG effects range from small and non-quantified to a reduction of more than 177 million metric tons of carbon dioxide emissions and 134 thousand tons of nitrous oxide emissions, the two main greenhouse gas components from fossil-fired conventional power generation, as well as 299,000 tons of sulphur dioxide emissions.

Reductions in air emissions are inputs to estimating changes in incidence rates of health effects and the associated economic valuation of those effects (the latter included in the NPV measures above) using the U.S. Environmental Protection Agency's (EPA) COBRA model (Co-Benefits Risk Assessment Model, described in U.S. EPA, 2006). To apply COBRA, it is necessary to enter the estimated changes in air emissions of particulate matter (PM), sulphur dioxide (SO_2), nitrogen oxide (NO_x), and volatile organic compounds (VOCs) into the model. Because not all air pollutants are taken into account by the model, the results obtained from using COBRA for the analysis are taken as a lower-bound estimate of the impact of health effects and their economic value.

In physical units, the health effects of the resulting reductions in air pollution (NOx, PM, and SOx) range from small and non-quantified to nearly a 1000 mortalities avoided, more than 1,450 non-fatal heart attacks avoided, and the avoidance of more than 120,000 work days lost due to sickness.

Estimating security benefits and costs

Attempts at monetary valuation of security benefits would be subject to far greater margins of error than for the other monetary estimates contained in the studies. For this reason, the 2009 recommended EERE approach was to avoid monetary estimates of security benefits, and, to the extent feasible, to use an estimate of the reduction in physical units of barrels of oil equivalent (BOE) deriving from use of renewable energy, increased efficiency, and energy conservation as a rough indicator of security benefits. This is one way, among others, to measure energy security. Security benefits are attributed to reducing disruptions in the nation's energy supply. They also are attributed to reducing threats to the nation’s energy infrastructure. In addition, and in the longer run, national security benefits may also result from reducing GHG emissions, by avoiding the host of overwhelmingly negative long-range national security consequences that have been predicted in response to global warming. These effects are extremely difficult to assign values--particularly economic values--with any confidence. Associations among changes in energy efficiency, energy supply, energy prices, and security impacts involve many assumptions, with causal relationships far more uncertain than for those entailed in estimating the other categories of benefits included in the 2009 studies and addressed by the related draft Guide.

Energy security effects found in the four studies range from small and non-quantified to an equivalent reduction of nearly 418 million barrels of crude oil, equivalent to a reduction of about 1 percent of the total crude oil imported by the United States from 1995 through 2007.

Estimating knowledge benefits

The creation and dissemination of knowledge outputs are central to EERE's R&D programs. These knowledge outputs embody the results of program R&D in papers, patents, presentations, models, resource maps, prototypes, technology demonstrations, test data, research tools, trained and experienced people, and networks of researchers working collaboratively. The take-up and use of these knowledge outputs by industry enables the production of more energy-efficient and environmentally-friendly products and new and improved renewable energy systems. Moreover, the acquisition of EERE knowledge outputs by the broader community appears to increase interest in and willingness to adopt energy innovations, and enables researchers in other organizations to make further advances.

The knowledge base created by an EERE program or subprogram is more extensive than that captured by the set of selected technologies assessed by the benefit-cost studies. Therefore, each study incorporates a fuller assessment of the program/subprogram's knowledge creation and dissemination. Techniques used to document knowledge creation and flow include bibliometrics (patent citation analysis and publication co-author and citation analysis); analysis of documents and databases; and interviews with experts.

Patent analysis has been used extensively to trace technological developments and is emphasized in the assessment of knowledge benefits for these studies. The analysis is in part quantitative in that patents and citations can be counted and statistical comparisons can be made at the organizational level and at the patent level. The patent analysis is based on the idea that the prior art embodied in a patent referenced by a later patent provides part of the foundation for the later invention. A correlation between patent citations and measures of technological and scientific importance has been documented; highly cited patents tend to contain technological information of particular interest or importance. A summary of validation studies supporting patent analysis for assessing knowledge benefits and dissemination is found in Breitzman and Mogee (2002).

Backward patent tracing is used in support of the four studies to determine the extent to which DOE-funded research in the program/ subprogram area has formed a foundation for technologies in the target area developed by leading commercial innovators in the industry. Forward patent tracing is used to investigate the impact of DOE-attributed patents resulting from the program/subprogram on subsequent technological developments, regardless of where they occur (whether in or outside the technology and industry area targeted by EERE's program).

The knowledge sections of the four 2009 benefit-cost studies were derived from four separate but related studies by Ruegg and Thomas (2009, 2010a-2010c) which traced linkages from the outputs of EERE's R&D programs to downstream developments. The results show that in the case of advanced combustion research, EERE's investment in combustion R&D generated a knowledge base that has helped to form a foundation for more than a dozen important technologies, including fuel injection, homogeneous charge compression ignition, exhaust gas recirculation, and low emissions diesel fuel. In geothermal, EERE's R&D investment yielded approximately 90 DOE-attributed patent families (where each family contains all patents based on the same invention) and more than 3,000 publications. Multiple technologies important to recent advances in producing power from geothermal resources and in increasing efficiency in gas and oil extraction trace back strongly through patents and publications to DOE-funded geothermal research. EERE's funding of solar PV research generated knowledge embodied in an estimated 274 patent families in solar PV and more than 900 publications. These patents and publications provide a knowledge foundation on which further innovations in solar energy have built, as well as innovations in the semiconductor industry more generally. All of the solar energy patents of the eight top U.S. solar PV producers are closely linked to earlier DOE-attributed solar PV patents, among them ECD (Uni-Solar), BP Solar, Global Solar, and SunPower. Evidence suggests that EERE-funded R&D in wind energy also created highly influential intellectual property in the wind energy industry, such as innovative airfoils for blades, retractable rotor blades, variable speed wind turbines, rotor control systems, and active pitch controls. It also created intellectual property in wind energy that is linked to innovations outside wind energy, such as power conversion systems, hybrid vehicles, and paper and pulp machinery.

Conclusion

The goals set for the new draft EERE retrospective benefit-cost methodology were met in the four studies completed early in 2010. In a fairly consistent manner the studies determined realized economic and other net benefits that (1) modeled government additionality in detail, on a case-by-case basis, (2) refined and expanded environmental benefits, particularly health benefits from reduced air pollution, (3) estimated security benefits as feasible, (4) expanded the quantitative treatment of knowledge benefits, and (5) calculated returns to selected technologies within a program cluster, i.e., a whole EERE program or subprogram, rather than to a single project. These characteristics constitute best practice and are not present in all benefit-cost studies.

Lessons have been learned during these four initial studies that will be incorporated into the final methodology Guide and future studies, as well as guidelines on routine collection of data that will improve future evaluation studies. The concern of expert reviewers that four categories of benefits were too many to address in a single study was disproved; however work still needs to be done to better integrate the four categories of benefits into the body of the report. Further, separate major efforts are necessary to develop and validate credible ways to monetize security benefits. Also analysis was hindered by the lack of historical cost data at the detailed level of the selected technologies.

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