U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Retrospective Benefit–Cost Evaluation of U.S. DOE Geothermal Technologies R&D Program Investments:

Impacts of a Cluster of Energy Technologies

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Any shortcoming or omissions in this report are the authors' responsibility.

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EXECUTIVE SUMMARY

This report presents the findings from a retrospective economic analysis of technology development supported by the U.S. Department of Energy's (DOE) Geothermal Technologies Program (GTP) in DOE's Office of Energy Efficiency and Renewable Energy (EERE). The purpose of this study is to estimate the "public" return on investment (EERE GTP's return on investment to the nation) by comparing historical economic activity with GTP's investment to what would have likely happened in the absence of EERE GTP. The study includes:

- An assessment of DOE's role in technology development and adoption,
- An estimate of the economic and environmental health benefits generated from selected technologies, and
- An estimate of measures of economic return from DOE's research and development (R&D) activities.

Geothermal energy systems tap into thermal energy in the earth to produce heat and electricity. Geothermal power is a viable alternative for traditional fossil fuel (e.g., coal) or nuclear base-load generation. It also has the advantage of being a clean, renewable energy source without the variability of other renewable sources, such as wind and solar. Resources of geothermal energy vary in quality and accessibility because of differences in depth of reservoirs, rock formations, and water content. Historically, geothermal power plants have been built under ideal conditions for energy production; usually where the reservoir is close to the surface, the host rock is permeable and porous, and the ground fluid saturation and recharge rates allow having economically feasible operation. The relative scarcity of high-quality natural geothermal sites has limited widespread geothermal energy use.

In the early 1970s, federally-sponsored geothermal R&D began with funding from the Atomic Energy Commission and the National Science Foundation. The GTP was initiated by DOE in the late 1970s to support the development of technologies that would improve the economics of tapping geothermal resources. Since that time, GTP has conducted a wide range of research targeted at the long-term goal of making geothermal energy a cost-competitive power production alternative. This study selected four technologies that accrued significant economic benefits for the geothermal industry and other industries (e.g., oil and gas) for detailed analysis:

- **Polycrystalline diamond compact (PDC) drill bits**. PDC drill bits use harder, longer lasting cutting surfaces and a simplified mechanical action; increasing both the productivity (more feet drilled per hour) and efficiency (less drill bits required per well) of drill bits.
- **Binary cycle power plant technology**. Binary cycle technology enabled the development of geothermal plants using low heat sources increasing geothermal capacity in place and offsetting electricity production by flash cycle technologies and a mix of fossil fuels.

- **TOUGH[1] series of reservoir models**. The TOUGH series of models is a family of computer numerical simulation programs used to track fluid and heat flow in porous and fractured media. These models helped to optimize the performance of geothermal resources and manage risk associated with the uncertainty of their performance.
- **High-temperature geothermal well cements**. High-temperature geothermal well cements offer an improvement over alternative cement technology. They have a life expectancy of up to 20 years, eliminating annual reworks of geothermal and carbon dioxide injection wells. By comparison, wells that use traditional cement need to be reworked every one to two years.

ES.1 Methodology

The analysis framework focused on four categories of net benefits to be assessed: economic, environmental, knowledge, and security. For each of the four geothermal technologies selected, a common approach was used for the evaluation. This approach included the following steps:

1. Conduct a historical review of the technology's development, demonstration, and commercialization (if applicable) to assess the R&D timeline and EERE's role.
2. Define the next best alternative technology.
3. Quantify the economic and environmental (air emissions) health net benefits by comparing the new (selected) technology to the next best alternative (independent of EERE attribution).
4. Determine the share of economic and environmental health net benefits attributable to DOE activities.
5. Calculate DOE program costs and estimate measures of economic performance.

In addition, a literature search and a series of interviews were conducted with industry and academic experts to estimate economic and environmental benefits attributable to DOE's activities for each of the four selected technologies. A bibliometrics and historical tracing framework was also used to investigate the knowledge output creation and dissemination from R&D conducted by DOE's GTP.

A cluster analysis was then used to obtain measures of economic performance for the GTP as a whole. This analysis compared the sum of the net benefits from the four technologies investigated with the total expenditures of GTP.

ES.2 Findings

The four technologies selected for analysis in this study reflect the wide range of research activities conducted by the Geothermal Technologies Program and, as a group, have generated significant economic, environmental, and knowledge benefits.

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[1] TOUGH is both an acronym for "Transport of Unsaturated Groundwater and Heat" and a reference to tuff formations in Yucca Mountain, which was one of the first major applications of the code.

ES.2.1 Economic Benefits

Polycrystalline diamond compact (PDC) Drill Bits: Approximately 60% of worldwide oil and gas well footage in 2006 was drilled using PDC drill bits (Blankenship, 2009). The main advantage of PDC drill bits over conventional roller cone bits is that they reduce the frequency of pulling the drill string to replace the drill bit, allowing higher penetration rates and thus reducing the time (and cost) of renting expensive drill rigs. The use of PDC drill bits in offshore applications in the oil and gas industry is estimated to reduce costs by $59 per foot drilled.

Binary Cycle: In reservoirs where the temperature range is 150°C to 190°C, flash cycle technology is economically viable but has approximately 15% lower electricity generation productivity as compared to binary cycle, because of its lower conversion efficiency. Thus, in this temperature range, the next best alternative is a traditional, but less productive, flash cycle geothermal plant.

TOUGH Models: Using reservoir modeling increased productivity of geothermal resources by an estimated 10%. These benefits are somewhat offset by additional exploration costs associated with reservoir modeling. However, in the aggregate, reservoir modeling has been profitable for the geothermal industry by improving subsurface exploration.

High-Temperature Cement: The rapid deterioration of Portland cement in geothermal wells (<12 months) resulted in frequent well workovers and costly well remediation. The use of high-temperature cements enhances performance in terms of structural stability and corrosion resistance and is estimated to eliminate $150,000 in annual well remediation costs and extend the working life of geothermal production wells to 20 years or more.

A summary of economic benefits attributed to DOE is presented in Table ES-1. Reduction in drilling costs associated with PDC drill bits accounts for the overwhelming share of the total economic benefits with present value (PV) of $8.1 billion (discounted at 7%) quantified as part of this study.

Table ES-1. Total Economic Benefits, 1980–2008

Technologies	Economic Benefits PV at 7% (thousands $2008)[a]	Percentage of Total Benefits
PDC drill bits	$7,813,212	96.7%
Binary Cycle	$42,848	0.5%
TOUGH Models	$219,445	2.7%
High-temperature cement	$1,013	0.0%
Total economic benefits for the four technologies	$8,076,518	100.0%

[a] PV = present value. PV base year is 1976.

ES.2.2 Environmental Benefits

Environmental benefits of geothermal plants make them valuable assets in reducing air pollutants such as particulate matter (PM), sulfur oxides (SO_x), and nitrous oxides (NO_x); and in reducing greenhouse gases (GHG), such as carbon dioxide (CO_2). Environmental health benefits were identified and quantified for binary cycle technology and the TOUGH system of models. The primary environmental benefits from binary cycle technology result from the additional renewable electricity generated from reservoirs where the temperature range is below 150°C, offsetting generation from a mix of fossil fuels. As for TOUGH model benefits, the increased productivity of geothermal fields' yields resulting from using simulation modeling generates additional renewable energy that offsets coal base-load fossil fuel generation.

The Co-Benefits Risk Assessment (COBRA) model was used to calculate the environmental health benefits associated with the reduction in air pollution resulting from using binary cycle technology and the TOUGH series of models. The input to the COBRA model is the reduction (tons/year) of PM, NO_x, and SO_2 resulting from geothermal energy compared to electricity that would otherwise be produced by coal, petroleum, and natural gas-fired power plants.

Table ES-2 presents a summary of the environmental benefits attributable to DOE. Present value of environmental health benefits for binary cycle technology and the TOUGH series of models are discounted at 7% total $23.0 million and $103.7 million, respectively.

Table ES-2. Environmental Health Benefits and Emission Reduction Attributed to DOE[a]

	Binary Cycle	**TOUGH Models**	**Total**
PM (short tons)	4,572	17,621	22,193
SO_2 (short tons)	1,903	7,710	9,614
NO_X (short tons)	998	4,039	5,037
GHG (thousand tCO_2e)	1,319	5,266	6,585
Monetized health benefit (PV at 7%, thousands)[b]	$22,970	$103,674	$126,644

[a] DOE attribution to these two technologies is explained in Sections 6.5 (Binary Cycle) and 7.5 (TOUGH Models) of the report.
[b] PV base year is 1976.
[c] Based on fossil fuel mix of 60% coal, 39% natural gas, and 1% petroleum

ES.2.3 GHG Effects

Environmental benefits attributed to DOE include reductions in GHGs of 6.6 million tons (see Table ES-2) of carbon dioxide equivalents (tCO_2e). Replacing fossil fuel electricity generation with geothermal power reduces GHG emissions. If cap and trade climate change policy is initiated in the future, the emissions could be monetized and included in the benefit-cost analysis.

ES.2.3 Knowledge Benefits

Principal conclusions drawn from assessing knowledge benefits resulting from GTP-funded R&D are many. The resulting knowledge base includes, among other things, approximately 90 DOE-attributed patent families (where each family contains all patents based on the same invention) and more than 3,000 publications. These patents and publications provided a noteworthy foundation for further innovation in the geothermal energy industry and also in the gas and oil industries. Multiple technologies important to recent advances in producing power from geothermal resources and increasing efficiency in gas and oil extraction trace back strongly through patents and publications to DOE-funded research.

Of a total population of more than 1,000 geothermal patent families assigned to numerous organizations, 21% were linked to earlier DOE-attributed geothermal patents and publications, second only to that for the patent portfolio of Chevron (24.9%), which is billed as the world's largest producer of geothermal energy. More than 40% of Chevron's patents have built extensively on earlier DOE-attributed geothermal patents and papers, as well as a high percentage of the patent portfolios of Ormat and other leading companies in geothermal energy.

Among the DOE-attributed patent families and publications are those describing Organic Rankine and Kalina thermodynamic cycles, the generation of geothermal energy from hot dry rocks, techniques for treating geothermal brine, advanced drill bits, downhole electronics and data transmission, improved cements to withstand conditions in wells, and other innovations describing geothermal power plants and power generation.

In addition to the knowledge base captured in patents, papers, models, prototypes, test data, and other tacit forms of knowledge, DOE-funded research has trained technologists and researchers in geothermal research across the nation and fostered the development of a network among them.

ES.2.4 Security Benefits

Security benefits derive from reducing the probability and potential impact of oil and natural gas disruptions and price shocks or other energy system disruptions that would damage or disrupt the economy, environment, or national security of the United States. Table ES-3 presents the reduction attributable to DOE. From 1980 to 2008, as a result of DOE's efforts, 24.3 million cubic feet of natural gas or 4.3 million barrels of oil equivalent were offset by geothermal energy.

Table ES-3. Security Benefits Attributed to DOE,[a] 1980–2008

	Binary Cycle	TOUGH Models	Total
Natural gas (million cubic feet)	4,863	19,401	24,264
BOE (thousand barrels of oil equivalent)	862	3,438	4,300

[a] DOE attribution to these two technologies is explained in Sections 6.5 (Binary Cycle) and 7.5 (TOUGH Models) of the report.

ES.2.5 Benefit-Cost Analysis for GTP (Cluster Analysis)

Table ES-4 presents a summary of the four GTP technology case studies. PDC drill bits had the highest net benefits with PV $7.8 billion, a benefit-to-cost ratio (BCR) of 295, and an internal rate of return (IRR) of 139%. High-temperature cement technology had the lowest net benefits (a negative value). This technology is in the early stages of adoption.

Table ES-4. Summary of GTP Technology Case Studies

Metric	PDC Drill Bits	Binary Cycle Plants	TOUGH Models	High-Temp Cement
PV[a] of total benefits at 7% (thousands $2008)	$7,813,212	$42,848	$219,445	1,013
PV[a] of program cost for selected case studies at 7% (thousands $2008)	$26,461	$26,819	$8,619	1,938
PV[a] of net benefits at 7% (thousands $2008)	$7,786,751	$16,029	$210,826	-925
PV[a] of net benefits at 3% (thousands $2008)	$18,473,186	$35,568	$446,302	162
BCR at 7%	295.3	1.6	25.5	0.5
BCR at 3%	451.4	1.9	39.3	1.1
IRR	139%	16%	48%	NA

NA = Not available

[a] PV base year is 1976. Benefits were accrued for following periods for each technology: PDC drill bits (1982–2008), binary cycle plants (1984–2008), TOUGH models (1980–2008), and high-temperature cement (1999–2008).

As shown in Table ES-5, research activities associated with these four technologies accounted for only 3.8% of GTP's budget from 1976 to 2008. Hence, it is very likely that the net benefits associated with GTP activities greatly exceed the $8.1 billion (discounted at 7%) quantified. However, it is still informative to compare the benefits from the four technologies to the total GTP expenditures to obtain lower bound measures of economic return.

Table ES-5. Summary of GTP Expenditures, 1976–2008

Technologies	Total Expenditures PV[a] at 7% (thousands $2008)	Percentage of Total
PDC drill bits	$26,463	1.6%
Binary Cycle	$26,819	1.6%
TOUGH Models	$8,620	0.5%
High-temperature cement	$1,934	0.1%
Total of four technologies	$63,836	3.8%
Total GTP expenditures	$1,660,194	100.0%

[a] PV base year is 1976.

The study used a cluster approach to generate a conservative estimate of economic performance for the GTP as a whole. The cluster analysis compared the aggregate benefits from the four selected technology areas to the investment costs of the entire program. As shown in Table ES-6, the cluster analysis yields net benefits with present value of $8.1 billion (discounted at 7%), a BCR of 4.9 (discounted at 7%), and an IRR of 22%.

Table ES-6. Benefit-Cost Analysis for the GTP Technology Case Studies (Cluster Analysis), 1980–2008

Metric	Value
PV[a] of total benefits at 7% (thousands $2008)	$8,076,518
PV[a] of total GTP cost at 7% (thousands $2008)	$1,660,194
PV[a] of net benefits at 7% (thousands $2008)	$6,416,324
PV[a] of net benefits at 3% (thousands $2008)	$16,969,002
BCR at 7%	4.9
BCR at 3%	9.2
IRR	22%

[a] PV base year is 1976.

Note that the study was retrospective in that only benefits and costs through 2008 were included. As a result, the measures of economic return calculated are likely to be conservative, because in many instances, DOE's historical R&D activities will continue to generate benefits well into the future.

ES.2.6 Sensitivity Analysis

When estimating the environmental health benefits attributed to DOE, it was assumed that in the absence of geothermal electricity, additional coal-, natural gas-, and petroleum-fired power plants would have been built to meet base load electricity demand. The exact mix of fossil fuels offset was calculated using the approach outlined in Appendix C. To investigate how sensitive our findings are to this approach, this study estimated environmental health benefits using an alternative scenario of 50% coal and 50% natural gas. The results are presented in Table ES-7. This alternative scenario is not based on specific information but is presented to illustrate how environmental benefits change when the offset fuel mix is changed.

Table ES-7. Environmental Benefits Attributed to DOE: Sensitivity to Displaced Fuel Type

	Displaced Generation		Percentage Reduction
	60% Coal, 39% NG, 1% Oil	50% Coal, 50% NG	
PM (short tons)	22,193	18,780	15.4%
SO_2 (short tons)	9,614	7,992	16.9%
NO_X (short tons)	5,037	4,227	16.0%
GHG (thousand tCO_2e)	6,585	6,268	4.8%
Monetized health benefit (PV[a] at 7%, thousands $2008)	$126,644	$107,501	15.1%

[a] PV base year is 1976.

The costs for TOUGH series of models and CaP cement technologies were estimated based on FTE estimates or DOE internal cost records, however, this information was not available for binary cycle plants and PDC drill bit technologies. The costs for two latter technologies were estimated based on relevant line items from overall GTP budget. A portion of line item expenses from the GTP budget was assigned to these two technologies. This approach likely overestimated PDC drill bit and binary cycle plant technology costs. To investigate how sensitive our findings are to this approach, this study lowered PDC drill bit and binary cycle plants technology costs by 50%. The resulting benefit-cost ratios are presented in Table ES-8. This alternative scenario is not based on specific information, but is presented to illustrate how PDC drill bit and binary cycle plant technology and overall benefit-cost ratios change when the cost calculation approach is changed.

Table ES-8. Sensitivity Analysis of GTP Technology Case Study Costs

Technology	Benefit-Cost Ratio at 7% (4 Case Study Technology Costs/4 Case Study Technology Benefits)	
	Baseline	Decrease PDC and Binary Costs by 50%
PDC drill bits	295.3	590.5
Binary Cycle	1.6	3.2
TOUGH Models	25.5	25.5
High-temperature cement	0.5	0.5
4 Case Study Technologies	126.5	217.1

1. INTRODUCTION

In the early 1970s, federally-sponsored geothermal research and development (R&D) began with funding from the Atomic Energy Commission and the National Science Foundation. This was followed by the Geothermal Energy Research, Development, and Demonstration Act of 1974. In 1977, the Department of Energy (DOE) assumed responsibility for federal geothermal R&D and shortly thereafter, created DOE's Geothermal Technologies Program (GTP) in DOE's Office of Energy Efficiency and Renewable Energy (EERE). The GTP mission is to support the development of technologies that would improve the economics of tapping less-than-ideal geothermal resources.

This report presents the findings from a retrospective economic analysis of the GTP. A cluster analysis was conducted for four selected technologies supported by the GTP. The objectives of the study were to:

- Assess DOE's role in technology development and adoption,
- Estimate the economic and environmental health benefits generated from selected technologies, and
- Compare benefits attributable to DOE's investments both for the GTP as a whole, and for the selected set of technologies examined in detail and estimate measures of economic return from DOE's R&D activities.

The study is retrospective in that only benefits and costs through 2008 are included in the analysis. As a result, the measures of economic return calculated in this report are conservative, because in many instances, DOE's historical R&D activities will continue to generate benefits well into the future. In addition, the nature of the cluster analysis (where total program costs are compared with benefits from a subset of selected technologies) contributes to the conservative nature of the empirical findings.

1.1 Selected Technologies

The GTP has made significant contributions to a wide range of technologies, enabling more effective operation and management of underground resources. This study selected four technologies that had prominent benefits in the geothermal industry and beyond:[1]

- **Polycrystalline diamond compact (PDC) drill bits**. Geothermal systems often require penetrating harder rock than the rock encountered when drilling oil and gas wells, which necessitated the development of improved drill bits. PDC drill bits, with their harder and longer lasting cutting surface, improved on existing drill bit technology allowing the return to a simpler mechanical action from more complex roller-cone action and increasing both productivity (feet drilled per hour) and efficiency (number of drill bits per hour). In the absence of the development

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[1] The technologies were selected based on a review of the published literature and DOE's historical summary reports (EERE/GTP [2010], EERE/GTP [2008a], EERE/GTP [2008b], EERE/GTP [2008c], and EERE/GTP [2008d]). The technologies were intended to capture significant contributions by DOE across the broad range of geothermal research conducted by the GTP.

of PDC drill bits, this study assumes (based on the interviews with experts) that industry would have continued to use the existing roller bit technology. Roller bits were an established technology and continue to be used where economically feasible (and where PDC drill bits fail). This occurs in hard and fractured rock, formations inter-bedded with stringers, and formations with hard inclusions such as chert.

- **Binary cycle power plant technology**. Binary cycle power plants are an improvement over existing geothermal plant technology and allow the construction of a geothermal plant in sites with lower temperatures that were previously unsuitable for geothermal generation. This technology enabled the development of geothermal plants using low heat sources, thus increasing geothermal capacity in place and offsetting electricity production that uses a mix of fossil fuels.
- **TOUGH[2] series of reservoir models**. The TOUGH series of models is a new technology representing modeling capabilities not previously available. Reservoir modeling is mainly used as an operating optimization process and, to a lesser extent, during plant design. The benefits of the TOUGH series of models of geothermal applications are reduced drilling costs and decreased uncertainty associated with well management. Because of the flexibility of the TOUGH models, they have also been used for nuclear waste storage, carbon capture and storage applications, and groundwater protection and remediation design of subsurface contamination.
- **High-temperature geothermal well cements**. High-temperature geothermal well cements offer an improvement over existing cement technology. They have a life expectancy of up to 20 years, eliminating annual reworks of geothermal wells. High-temperature cements have also been used in CO_2 injection wells on enhanced oil recovery projects and in capping retired offshore oil and gas wells. The next best alternative would have been to use existing cements (Portland cement).

These technologies and their developmental timelines are discussed in detail in the individual case studies presented in Chapters 5 through 8 of this report.

1.2 Report Structure

The remainder of the report is structured as follows:

- **Chapter 2 – Background:** provides an overview of the GTP's research and discusses many of the drivers for geothermal projects over the last 40 years.
- **Chapter 3 – Methodology:** provides an overview of the common methodology used in the four case studies.
- **Chapter 4 – Summary Results:** presents an overview of the study findings, including measures of economic return for each of the four technologies selected, as well as a cluster analysis that presents conservative estimates of economic return for the GTP as a whole.
- **Chapters 5 through 8:** present the individual technology case studies.
- **Chapter 9:** provides a discussion of the knowledge benefits associated with the GTP.
- **Appendix A:** describes a role for government in technology development.

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[2] TOUGH is both an acronym for "transport of unsaturated groundwater and heat" and a reference to tuff formations in Yucca Mountain, which was one of the first major applications of the code.

- **Appendix B:** provides information on the interviews conducted for this study.
- **Appendix C:** provides a description of the COBRA model and describes the data used to estimate environmental health benefits in the analysis.
- **Appendix D:** provides GTP’s historical cost (program funding) data used in the benefit-cost analysis.
- **Appendix E:** explains the bibliometrics methodology used in the knowledge benefits chapter.

2. BACKGROUND

Geothermal energy systems tap into hydrothermal energy in the earth to produce electricity. Geothermal energy has the advantage of being a clean, renewable energy source without the variability of other renewable sources, such as wind and solar. It is also a viable alternative for traditional fossil fuel (e.g., coal) base-load generation, particularly coal and natural gas.

Resources of geothermal energy vary in quality and accessibility due to differences in depth of reservoirs, rock formations, and water content. Historically, geothermal power plants have been built under ideal conditions for energy production – usually where the reservoir is close to the surface, the host rock is permeable and porous, and the ground fluid saturation and recharge rates allow having economically feasible operation. The relative scarcity of such ideal geothermal sites has been a barrier to widespread geothermal energy use (U.S. DOE, 2008a).

The Department of Energy initiated the Geothermal Technologies Program in the late 1970s and has conducted a wide range of research targeted at the long-term goal of making geothermal energy a cost-competitive power production alternative. For example, before research efforts by the GTP, little commercial geothermal power was generated in the United States from the predominantly liquid-dominated hydrothermal resources.[1] Only four plants were installed from 1971 to 1979 (as compared to 16 plants from 1980 to 1985).

The United States currently leads the world in online megawatt capacity of geothermal energy and electric power generation (Glitnir, 2008). However, the net electricity generated from geothermal power in the United States in 2008 was 14,859 million kWh, or only 0.37% of the total electricity generated in the United States that year (U.S. DOE, 2010d). As shown in Table 2-1, the overwhelming majority of installed geothermal capacity is in California and Nevada (due to the abundance and ease of access to the heat sources in these states).

Table 2-1. Geothermal Power Capacity by State, 2008

State	Installed Capacity (MW)	Share by State
California	2,555.3	87%
Nevada	318.0	11%
Utah	36.0	1%
Hawaii	35.0	1%
Idaho	13.0	<1%
Alaska	0.4	<1%
New Mexico	0.2	<1%
Total	2,957.9	100%

Source: U.S. Geothermal Energy Association (2009).

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[1] Liquid-dominated resources are those in which liquid has not vaporized into steam (as opposed to vapor-dominated resources).

2.1 Drivers for Geothermal Power

Limited commercial geothermal electric power production in the United States began in the 1960s. However, following the energy crisis in the 1970s, the development of geothermal resources in the United States became a national priority, and federal and state resources were made available to support R&D and promote implementation projects. As a result, the growth in installed capacity through the 1980s and 1990s was in large part driven by political and financial support. Table 2-2 lists various federal and state policy initiatives that have contributed to the continued development of new geothermal energy resources. These policies have been instrumental in enhancing the economics of exploration, drilling, and siting new geothermal projects; and stimulating geothermal investment from the private sector. The role of government in technology development is further described in the Appendix A.

The economic and environmental benefit estimates associated with DOE activities are related primarily to lowering installation and operating costs, and increasing operating efficiencies and productivity. The exception is DOE's impact on the adoption of binary cycle technologies, where GTP's funding and demonstration projects proved the technology and accelerated its adoption.

2.2 Overview of GTP Research

In four reports issued by GTP under the main title "A History of Geothermal Energy Research and Development in the United States," GTP identifies the four main areas of geothermal technology development and research: drilling, exploration, reservoir engineering, and energy conversion. This section discusses the history of the GTP program and describes each of the four main areas of their research.

Prior to 1974, the majority of research on geothermal technology was conducted by government agencies, including the National Science Foundation, Atomic Energy Commission, U.S. Geological Survey (USGS), and the Energy Research and Development Administration (Reservoir Engineering, 2008). In 1974, the U.S. government enacted the Geothermal Energy Research, Development and Demonstration (RD&D) Act. This Act instituted the Geothermal Loan Guaranty Program, which provides investment security to the public and private sectors to exploit geothermal resources (EERE/GTP, 2010). The Energy Research and Development Administration (ERDA) was formed in 1975, and its Division of Geothermal Energy took over the RD&D program. When DOE was formed in 1977, it took over as the leading agency in geothermal technology research (EERE/GTP, 2008a).

Table 2-2. Federal and State Policy Initiatives in Geothermal Energy

Year	Initiative
1978	The Federal Public Utilities Regulatory Policies Act required utilities to purchase power from small renewable energy producers, referred to as Qualifying Facilities, at the utilities' avoided cost. This legislation spurred growth in a number of new renewable and cogeneration energy projects, most notably in California (Masters, 2004).
	The Federal Energy Tax Act provided a 10% corporate tax credit for investment in geothermal and other renewable energy sources.
1980	The California Geothermal Resource Development Account provided funding to support the development of new and existing geothermal resources in California.
1983	California Standard Offer Contracts were enacted to allow state energy utility companies to enter into long-term, fixed price contracts with renewable generating facilities for periods of 10 to 30 years. This provided long-term, fixed price contracts, lowering return uncertainty and making it easier for geothermal developers to obtain requisite financing (REPP, 2003).
1986	The Federal Tax Reform Act repealed the 10% tax credit for investment in renewable energy generation projects.
1992	The Energy Policy Act reinstated the 10% tax credit, but only for renewable energy production equipment.
1996	The California Public Goods Charge mandated a fee assessed on all energy bills starting in 1998, providing funding for renewable energy and technology development and demonstration.
2001	The Nevada Universal Energy Charge, similar to California's Public Goods Charge, allowed Nevada state utilities to assess a fee for providing renewable energy.
2002	The California Renewable Portfolio Standard Program required a 1% annual increase in renewable energy production by state utilities, up to 20% by 2017.
	The California New Renewable Resources Account provided financial resources to subsidize the cost of producing energy above the government-issued market price of the Renewable Resource Trust Fund.
	The Nevada Renewable Portfolio Standard required state electric utilities to generate or purchase >5% of electricity sold from renewable energy sources, increasing to 15% by 2013.
2004	The Federal Production Tax Credit, a statute originally introduced under the Energy Policy Act of 1992, was expanded under the American Jobs Creation Act of 2004 to include renewable energy production from geothermal facilities. The production tax credit provided a tax credit to renewable energy generators for the production and sale of electricity to consumers. The federal production tax credit has expired and been renewed and expanded numerous times since 1992, most recently in 2009. The original tax credit was 1.5 cents per kWh produced (1992 dollars) (U.S. DOE, 2005b).

2.2.1 Drilling

ERDA, and later DOE, funded drilling R&D as part of government support for geothermal research in the United States, with some costs shared with industry partners. At the inception of DOE's efforts in the 1970s, DOE program managers were responsible for as many as 20 drilling projects. By the early 1980s, Sandia National Laboratories (SNL) assumed responsibility for DOE's drilling technologies program, with some of the work being done at Los Alamos National Laboratory (LANL) (EERE/GTP, 2008a).

The cost of completing and drilling wells is a major component of the capital investment in a geothermal power plant for both production and reinjection. Research to reduce this cost has been underway since 1975. The primary focus of the DOE research has been to pursue two goals (EERE/GTP, 2008a):

- Develop technologies to lower geothermal drilling costs in the near term.

- Pursue high-risk, long-term R&D activities on advanced concepts that would lead to significant long-run reductions in drilling costs.

Table 2-3 summarizes drilling research and development projects carried out by DOE and national laboratory researchers.

Table 2-3. DOE Drilling Research and Development Project Categories, 1976–Present

Project Category	Description	Major Projects
Rock penetration	Drilling methods suitable for harder, more abrasive formations characteristic of geothermal reservoirs with the goal of increasing drilling speed and reducing drill wear.	Spark Drill (1976–1979), Improved Roller-Cone Bits (1975–1980), Chain Bit (1978–1991), Bit Hydraulics (1979–1982), PDC bits (1978–Present), Percussion Drilling (1980–1981), Jet Erosion Drilling (1979–1981), Cavitating Mud Jets (1979–2005)
Other drilling tools	Tools that improve the environment in which drill bits operate, improving drill bit performance.	Motor Seals (1976–1982), Insulated Drill Pipe (1986–1999), Diagnostics-While-Drilling (1999–2005), Drilling Dynamics Simulator and Active Vibration Control (2004–Present)
Logging and instrumentation	Instruments that provide downhole data that characterize reservoir conditions and drill performance.	High-Temperature Electronics (1976–2007), Wellbore Inertial Navigation System (1980–1982), Downhole Radar (1984–1990), Bore-Hole Televiewer (1980s–1990s, 2003–2005), Acoustic Telemetry (1986–2003), Spectral-Gamma Logging Tool (1993–1997), Precision Pressure-Temperature Tool (1993–1998), Downhole Steam Sampler (1995–2007), Core Tube Data logger (1998–2000), Downhole Data Logger (2002–2003), Optical Fiber (1999–2002), Downhole Turbine-Alternator (2001–2003), Downhole Monitoring System for the USGS and Coso (2002–2005)
Drilling fluids and wellbore integrity	Technologies that battle drilling problems (such as lost circulation of drilling fluid, stuck drill pipe, damaged bits, slow penetration rates, and collapsed boreholes).	High-Temperature Muds (1979–1988), Lost Circulation Materials Qualification (1979–1989), Drilling With Aqueous Foam (1979–1980s), Inert Gas Generation and Drilling Corrosion (1979–1982), High-Temperature, High Pressure Viscometer (1979–1981), Polyurethane Foam Grout (1980s–2004), Drillable Straddle Packer (1989–1999), Rolling Float Meter (1991–1998)
Slimhole drilling	Technologies that allow drilling smaller exploration holes (2 to 6 inches compared to 8.5- to 12.25-inch holes drilled historically), reducing drilling costs.	Steamboat Hills: Nevada Demonstration (1993), Vale: Oregon Demonstration (1994), Newberry Caldera, Oregon Demonstration (1995), Fort Bliss: Texas Demonstration
Systems analysis	Technologies to address complex problems by breaking them into smaller components and solving each component individually.	Geothermal Well Models (1980–1982), Cost Models (1980s–Present), Advanced Drilling Systems (1995–1996), Slimhole Power Generation (1994–1996), Drilling For Geothermal Heat Pump Installation (1996), Wellbore Lining (2001–2002)

(continued)

Table 2-3. DOE Drilling Research and Development Project Categories, 1976–Present, (continued)

Project Category	Description	Major Projects
Analytical studies	Software tools that could be applied in different scenarios to single out the impact of a particular technological advancement.	GEOTEMP (1979–1984), Casing Stress and Collapse (1981–1985), Drill-String Dynamics (1981–1987)
Geothermal Drilling Organization (GDO)	The organization created in 1982 to develop and fund near-term technology development project.	Expert System for Lost Circulation (1996–1999), Retrievable Whipstock (1996), Rotating-Head Rubbers (1996–1997), Valve-Changing Tool (1997), Insulated Drill Pipe (1997–1999), Geysers Casing Remediation (1998–1999), Low Emission Atmospheric Metering Separator (1998–2000)
Scientific drilling management	Cross-agency drilling management and technical support performed by SNL, which benefited DOE's drilling research.	Inyo Domes and Craters (1987), Valles Caldera, VC-2B (1988), Weeks Island (1994), Long Valley, Phase 3 (1998)

Source: EERE/GTP (2008a).

2.2.2 Exploration

DOE's exploration research was initiated by several national laboratories beginning in the 1970s. Initially, research was conducted by universities and contractors. Since the 1980s, most of the work has been conducted by the University of Utah Earth and Geoscience Laboratory, Lawrence Berkeley National Laboratory (LBNL), and Lawrence Livermore National Laboratory (LLNL). Additional support was provided by Idaho National Laboratory (INL), Oak Ridge National Laboratory (ORNL), LANL, and SNL (EERE/GTP, 2008b).

DOE found that the most efficient way to promote the development of geothermal resources was to have a strong working relationship with the private sector. All of the research was driven by the industry's need to mitigate highest-risk and highest-cost elements of geothermal resource development. Research programs and projects have been selected based on the projected impact on program goals, especially related to cost of power. To this end, lowering well-field costs through dry-hole avoidance and improving drilling technology were identified as priorities in the increased development of the available hydrothermal resource base. Thus, most of the research work in the exploration area has been focused on these factors (EERE/GTP, 2008b). Table 2-4 summarizes exploration R&D projects carried out by DOE and national laboratory researchers.

Table 2-4. DOE Exploration Research and Development Project Categories, 1976–Present

Project Category	Description	Major Projects
Industry cooperative exploration and drilling	Case studies, cooperative exploration, and drilling aimed at lowering drilling costs.	Industry Coupled Case Study Program (1978), Cove Fort – Sulphurdale (1975–1979), Roosevelt Hot Springs (early 1970s–1979), Case Studies of Low- to Moderate-Temperature Hydrothermal Energy Development (1977–1978), Cascades I and II Cost Shared Programs, GRED I, II and III Cost-Share Programs
State Cooperative resource assessment	Prepared geothermal potential maps for western states.	State Coupled Program, State Cooperative Reservoir Analysis Program, Low-Temperature Resource Assessment Program
Selected hydrothermal system studies	Conducted topical studies of various geothermal environments.	Mid-Oceanic Volcanic Environments – Ascension Island, Deep Circulation within the Basin and Range Province – Coso Hot Springs, Geysers Coring Project, Deep Circulation within the Basin and Range Province – Dixie Valley, An Active Rift Valley – the Salton Sea Scientific Drilling Program
Geological technique development	DOE-funded studies documented the importance of hydrothermal alteration on the formation of geothermal systems and their impact on geophysical measurements.	Evolution of the Salton Sea Geothermal Field, structural controls on geothermal systems, applied terrestrial remote sensing technology, a conceptual model of volcano-hosted vapor-dominated geothermal systems, significance of hydrothermal alteration assemblages, duration and age of hydrothermal activity
	Surveys and studies related to geochemical analysis of reservoirs.	Trace-element analyses of soils and rocks, soil-gas and gas-flux measurements, geochemical analyses of geothermal fluids, fluid inclusion studies
	Surveys and studies related to geophysical analysis of reservoirs.	Seismic methods, aeromagnetic methods, gravity methods, thermal methods, geophysical well log interpretation, electrical methods, borehole geophysics studies, InSAR studies, geopositioning satellite studies, coupled reservoir simulation and electrical surveys
Exploration strategies	Developed geothermal exploration strategies.	
Resource assessment	Sponsorship of assessment the geothermal energy resource base in the U.S. by the USGS.	

Source: EERE/GTP, 2008b.

2.2.3 Reservoir Engineering

The research projects related to reservoir engineering began in 1976 and were carried out by a variety of institutions, including the national laboratories, universities, the USGS and the private sector. DOE's work in this field was focused on three general areas (EERE/GTP, 2008c):

- Improvement of existing technologies to enhance operation and management of geothermal resources by predicting resource productive capacity and longevity (such as reservoir simulation, tracer development and interpretation, reservoir monitoring, and establishing physical and chemical properties of reservoirs and reservoir fluids);
- Research and development of innovative technologies for heat extraction (hot dry rock, enhanced geothermal systems); and

- Site-specific cooperative studies with U.S. and international researchers to improve reservoir productivity (included theoretical, modeling, laboratory, and field activities related to demonstration and verification of geothermal resources).

Table 2-5 summarizes reservoir engineering research and development projects carried out by DOE and national laboratory researchers.

Table 2-5. DOE Reservoir Engineering Research and Development Project Categories, 1976–Present

Project Category	Description	Major Projects
Reservoir engineering	Developed reservoir simulators and geothermal modeling capability. Demonstrated reservoir simulators on numerous case studies and presented in educational meetings. Laboratory determination of reservoir, rock, and fluid parameters.	Reservoir modeling, physical properties and modeling parameters
Geoscience support projects	Discovered the appropriate tracers for use in hot geothermal reservoirs. Developed a better understanding of fluid geochemistry. Improved fluid-rock chemical interaction models. Monitored induced seismicity at two EGS projects and at The Geysers Geothermal Field.	Tracer development, fluid chemistry, induced seismicity
Enhanced geothermal systems	Completed the first ever enhanced geothermal system project at Fenton Hill. Performed joint feasibility project with industry to study EGS at the Coso Hot Springs Geothermal Field. Performed joint cost project with industry to study the feasibility of EGS at the Desert Hot Springs Geothermal Field. Performed research into alternative EGS working fluids to increase the feasibility of the process.	Fenton Hill, Coso Hot Springs, Desert Peak, Advanced Systems

Source: EERE/GTP (2008c).

2.2.4 Energy Conversion

When the DOE energy conversion R&D program first began, commercial power production from geothermal resources was limited to The Geysers, a dry-steam plant located in northern California. There was increasing interest in developing geothermal resources; however, since vapor-dominated resources (like The Geysers) are rare, developing the technologies to improve the economic feasibility of using liquid-dominated resources for power production became a primary focus of DOE research (EERE/GTP, 2008d).

A wide range of activities related to energy conversion were conducted in the early research period, with primary emphasis placed on understanding geothermal fluid chemistry and developing materials and components. Geothermal fluids produced from liquid-dominated resources are hot and may contain significant levels of dissolved solids with a higher potential for corrosion and scaling. Thus, DOE's research focused on identifying compatible materials and minimizing the precipitation of dissolved solids, since these factors determine the feasibility of using liquid-dominated resources for power production

(EERE/GTP, 2008d). Table 2-6 summarizes reservoir engineering research and development projects carried out by DOE and national laboratory researchers.

Table 2-6. DOE Energy Conversion Research and Development Project Categories, 1976-Present

Project Category	Description	Major Projects
DOE test facilities and demonstration plants	Developed government-owned test facilities, funded design and construction of demonstration geothermal power plants.	Raft River (1975), Geothermal Components Test Facility (1976), Geothermal Loop Experimental Facility (1976), Heber Binary Demonstration Plant (1980), Pleasant Bayou – Hybrid Geo-pressured Geothermal Power Plant (1989), Small-Scale Field Verification Projects (2000–2001)
Materials development	Developed cost-effective materials to meet the unique needs of geothermal applications.	Early materials and fouling studies, thermoplastic coatings – polyphenylene sulfide with additives, advanced coating materials (nano-composite coatings, coatings for air-cooled condensers, coatings for steam separators, heat exchanger tube joints), thermal spray coatings for piping surfaces
Geothermal fluid chemistry	Research focused on improving the understanding of geothermal fluid chemistry and particularly the formation and control of silica scale.	Silica scale inhibition (high-temperature, high-salinity geothermal fluids, chemistry instrumentation development, fluid sampling and analysis), treatment of geothermal brines, recovery of minerals and metals from geothermal brines
Power plant design and engineering	Research to lower power generation costs including work to develop innovative plant components and more efficient power cycles. Recently, research sought to enhance component performance to increase plant output and lower power generation costs.	Component development projects (innovative heat exchangers, total flow devices, enhanced air-cooled condenser performance, advanced direct contact condenser, component development for ammonia/water power cycles, non-condensable gas removal for steam plants), power cycle development (heat cycle research program, binary cycle improvement – post heat cycle research)
Power plant operations	Research aimed at improving process monitors or instruments to provide real-time monitoring of conditions affecting plant performance, cost, or the integrity of plant components (corrosion and scaling) for flash and steam plants. Research aimed at reducing the effects of high ambient temperatures on the performance of air-cooled binary plants and in lessening the adverse impact of NCGs in binary cycle working fluid systems on both plant output and operating and maintenance costs for binary plants.	Improved monitors (plant process stream monitors, monitoring biological activity, nondestructive testing of corrosion/erosion in piping systems), non-condensable gas removal system for binary plants, off-design operation of air-cooled binary plants (mitigating effects of off-design operation, evaporative cooling enhancement methods for air-cooled plants)
Power plant analytical studies	Studies that showed the benefits of specific technologies or concepts, providing the basis or justification for further research.	Geothermal sourcebook, next generation geothermal power plants, Geothermal Electricity Technology Evaluation Model (GETEM)

Source: EERE/GTP (2008d).

3. METHODOLOGY

The objective of this study is to assess the realized economic and other net benefits from the GTP. For each of the four geothermal technologies selected (PDC drill bits, binary cycle technology, the TOUGH family of reservoir models, and high-temperature cement), a common approach was used for the evaluation. This approach included the following steps:

1. Conduct a historical review of the technology's development, demonstration, and commercialization (if applicable) to assess the R&D timeline and EERE's role.
2. Define the next best alternative technology.
3. Quantify the economic and environmental (air emissions) health net benefits by comparing the new (selected) technology to the next best alternative (independent of EERE attribution).
4. Determine the share of economic and environmental (air emissions) health net benefits attributable to DOE activities.
5. Calculate DOE program costs and estimate measures of economic performance for each of the four research areas.

The above steps resulted in individual measures of economic performance for investment in each of the four technologies. A cluster analysis was then used to obtain measures of economic performance for the GTP as a whole. The cluster analysis compared the sum of the net benefits from the four technologies investigated with the total expenditures of the GTP.

The remainder of this chapter provides additional details on the methodology used in the analysis. This methodology follows the guidelines set forth in the draft *Guidelines for Conducting Retrospective Benefit-Cost Studies* (Ruegg and Jordan, 2009), and the discussion below borrows from that study.

3.1 Categories of Benefits

The analysis framework focused on four categories of net benefits to be assessed: economic, environmental, knowledge, and security, which are described further below.

- **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 cost, and by developing novel goods and services that provide desired new capabilities and experiences with economic value.
- **Environmental benefits** in EERE benefit-cost studies focus on air pollution, and the benefits are measured using changes in the physical quantities of a set of air emission pollutants. Monetary estimates are developed for environmental health benefits (reduced mortality, lost work days, and health care costs) using the Co-Benefit Risk Assessment (COBRA) model.[1] The input to the model is the reduction (tons/year) of PM, NO_x, and SO_2 from geothermal energy generated by binary cycle

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[1] A discussion of the COBRA model is contained in Appendix C.

compared to the next best alternative. The power displaced by geothermal energy depends on the electricity portfolio of each state. Shares of fossil fuels (coal, petroleum, and natural gas) displaced by geothermal energy are calculated in Appendix C. Reduction in the amount of PM, NO_x, and SO_2 (tons/years) are presented in Chapters 6 and 7. Reductions in GHG emissions are also estimated (but not monetized) and reported in tons of carbon dioxide equivalents (tCO_2e).

- **Knowledge benefits** for the 2009 benefit-cost studies were derived from parallel historical tracing evaluation studies that were prepared for each of the four program areas. The approach emphasizes analysis of the creation and dissemination of explicit knowledge codified in publications and patents but also provides qualitative information on relational networks and tacit knowledge. An overview of the methodology used in the analysis of knowledge benefits is presented in Appendix E.
- **Security benefits** derive from reducing the probability and potential impact of oil and natural gas disruptions and price shocks or other energy system disruptions that would damage or disrupt the economy, environment, or national security of the United States (Ruegg and Jordan, 2009). Security benefits are reported in terms of volumes of oil (gallons) and natural gas (cubic feet), which would otherwise be required to generate electricity equal to the amount generated as a result of DOE's support of the four case study technologies.

The monetized impact measures of economic and environmental health benefits are derived from retrospective analysis. This means that technologies for which monetary benefits are included in the study completed successful development and were deployed by the end of 2008. Prospective benefits beyond 2008 are highly likely to occur as a result of DOE/GTP research but are not included in the analysis because of the uncertainty around future operations of geothermal plants or oil and gas drilling activities. Performing the study retrospectively reduces the technical and market uncertainty that typically characterizes prospective benefit-cost analyses of advanced technologies.

3.2 Next Best Alternative

Benefits were calculated following methodologies pioneered by Griliches (1958) and Mansfield et al. (1977). This approach uses primary and secondary research on technology advances supported by DOE and ascertains how, when, or if those advances would have been made in the absence of DOE's programs.

The economic and environmental benefits of a new technology are judged against the next best alternative (i.e., the best choice that could be made in lieu of choosing the new technology). For a retrospective benefit-cost analysis, the next best alternative is defined by looking back in time and hypothesizing what technologies would have been developed or used in the absence of the new technology being investigated. This is sometimes referred to as a counterfactual scenario and is a key driver in quantifying benefits.

3.3 Attribution

Because this study focuses on estimating the return on DOE's investment (i.e., the return on public investment), it is important to identify EERE's role in realizing the benefits described above. To estimate the return on public investment, the impacts attributable to DOE needed to be estimated. This is also sometimes referred to as “program additionality.” This step – also counterfactual in nature – looks at what likely would have happened without the GTP’s activities (note the distinction that the benefit estimates described in Section 3.2 investigate the world with and without the new technology). Attribution assesses how (or if) the new technology would have evolved in the absence of the GTP’s activities.

A DOE R&D program might have a number of effects on technology development, but not all are relevant to all technologies. For the four geothermal technologies selected for this study, an R&D program may:

- Accelerate technology entry into the marketplace by speeding the R&D effort (which is then carried forward), reducing the risk of failure, enhancing the attraction of other funding for development and commercialization, and increasing market awareness;
- Improve the performance characteristics of the technology by increasing the scale or scope of the R&D effort to take on more technical challenges, and/or open technology opportunities that were not previously available;
- Change the cost of a technology by encouraging collaborative R&D activities among organizations to avoid investment redundancy, and providing specialized facilities and services needed by an entire industry in order to make advances; and
- Increase market size by reducing barriers to market adoption through information, training, standards and certification activities, and increasing the access of U.S. firms to growing global markets.

The determination of attribution is frequently one of the main sources of uncertainty in the benefit-cost analysis. Issues naturally stem from the multiple lines of evidence that are available to support claims of DOE additionality and the extent to which these lines of evidence come from unbiased, independent sources. Data collection in any retrospective evaluation presents challenges that limit evidence, such as lost or nonexistent records, key people who cannot be found or choose not to respond to inquiries, and industry concerns about sharing proprietary data. To address these issues, this study conducted multiple interviews with academics, industry experts, and GTP staff who were involved in the research, development, and deployment of the technologies.

3.4 Measures of Economic Performance

Once the share of net economic and environmental health benefits attributable to the GTP was quantified in dollar terms, the share was compared to program costs (expenditures) to develop measures of economic performance. As recommended in the DOE’s guidance document (Ruegg and Jordan, 2009), this study used three measures that are widely used to express the economic performance of the monetized elements of an evaluated investment:

- **Present Value (PV) of Net Benefits:** PV of net benefits is the lump-sum, time-equivalent dollar value of all the economic benefits less all the costs stated as of the base year (i.e., the first year of EERE investment in the technology or cluster). A positive PV of net benefits means that the benefits are sufficient to cover all costs plus the required rate of return expressed by the discount rate used to calculate the PV of net benefits. The larger the net benefits, the greater the extent that benefits exceed costs and the more worthwhile a project is considered, other things being equal. Out calculations placed cash flows in the middle of the period. The reason is that almost all of the DOE geothermal expenditures were labor costs (FTEs) that were distributed evenly over the year. This is slightly different from a standard one-time capital investment where the costs are incurred at the beginning of the time period. Similarly, geothermal benefits are associated with continuous activity, such as energy production (MWh/year) or operating cost reduction ($$/year). These benefits accrue close to evenly over a given year and hence the timing is best represented by the midpoint of the year.

- **Benefit-to-Cost Ratio (BCR):** The BCR is a ratio of benefits to costs and is a dimensionless number that indicates how many dollars of benefit are returned per dollar invested, adjusting for the time-value of money. It is computed by dividing total discounted benefits by total discounted costs. A ratio greater than one means that benefits exceed costs. A ratio of 10, for example, means that, on average, 10 dollars in benefits are generated for every dollar of costs incurred, after adjusting for the time-value of money.
- **Internal Rate of Return (IRR):** The IRR gives the rate of return on investment, expressed as an interest rate. Unlike the previous two measures, the discount rate is not used directly in the IRR calculation. Rather, the IRR is solved for by substituting an interest rate (i) with unknown value in place of the discount rate in the discounting formulas and solving for the value of i for which time-adjusted benefits equal costs (i.e., the discount rate for which net benefits are zero).

3.5 Benefit-Cost Analysis for the GTP (Cluster Analysis)

The aggregate benefits from the four selected technology areas are then compared to the GTP costs as a whole. This approach is commonly referred to as a cluster analysis. The purpose is to provide an estimate of the minimum return for the whole program, without performing detailed analysis of all of its research projects or technologies. The same three measures of economic return presented in Section 3.4 were used in the cluster analysis. For additional discussion of the benefits of cluster analysis and the rationale for using it, see Ruegg and Jordan (2009).

4. SUMMARY OF FINDINGS

This chapter presents an overview of the findings for the four technology case studies, as well as the cluster analysis for GTP as a whole. Primary and secondary data collection was conducted for each of the technologies. As part of the study, 22 informal interviews were conducted with industry experts, academics, and DOE staff. Appendix B lists the number of interviews conducted for each technology, and professional publications and technical reports are listed in Chapter 10. The calculations of the findings presented in this chapter are explained in greater detail in subsequent sections.

4.1 Individual Technology Case Studies

The analysis for each technology is summarized in this section[1], and additional detail is provided in Chapters 5 through 8. Table 4-1 presents the benefits and GTP expenditures for each of the four technologies, along with the calculated measures of economic return.

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[1] Knowledge benefits are discussed as part of the cluster analysis in Chapter 9. Knowledge benefits were analyzed for the GTP as a whole and not on an individual technology basis.

Table 4-1. Net Benefits Attributable to DOE (thousands $2008)

	PDC			Binary			TOUGH			Cement		
Year	**Total Benefits**	**Program Expenses**	**Net Benefits**	**Total Benefits**	**Program Expenses**	**Net Benefits**	**Total Benefits**	**Program Expenses**	**Net Benefits**	**Total Benefits**	**Program Expenses**	**Net Benefits**
1976	$0	$2,081	-$2,081	$0	$2,036	-$2,036	$0	$797	-$797	$0	$142	-$142
1977	$0	$2,081	-$2,081	$0	$2,036	-$2,036	$0	$797	-$797	$0	$142	-$142
1978	$0	$2,081	-$2,081	$0	$2,036	-$2,036	$0	$797	-$797	$0	$142	-$142
1979	$0	$2,081	-$2,081	$0	$2,036	-$2,036	$0	$797	-$797	$0	$142	-$142
1980	$0	$2,081	-$2,081	$0	$2,036	-$2,036	-$3,158	$797	-$3,955	$0	$142	-$142
1981	$0	$2,081	-$2,081	$0	$2,036	-$2,036	$7,041	$797	$6,244	$0	$142	-$142
1982	$319,823	$2,081	$317,742	$0	$2,036	-$2,036	$3,495	$797	$2,698	$0	$142	-$142
1983	$400,600	$2,081	$398,519	$0	$2,036	-$2,036	-$6,065	$797	-$6,862	$0	$142	-$142
1984	$630,196	$2,081	$628,115	$2,114	$2,036	$78	$10,446	$797	$9,649	$0	$142	-$142
1985	$662,306	$2,081	$660,225	$2,047	$2,036	$11	$6,455	$797	$5,658	$0	$142	-$142
1986	$436,938	$2,081	$434,857	$9,822	$2,036	$7,786	$21,896	$797	$21,099	$0	$142	-$142
1987	$443,817	$1,844	$441,973	$14,398	$1,639	$12,759	$21,946	$797	$21,149	$0	$142	-$142
1988	$474,236	$1,683	$472,553	$3,750	$1,335	$2,415	$15,404	$797	$14,607	$0	$142	-$142
1989	$465,778	$1,601	$464,177	$8,238	$1,015	$7,223	$28,656	$797	$27,859	$0	$142	-$142
1990	$619,142	$1,490	$617,652	$15,229	$1,025	$14,204	$38,331	$797	$37,534	$0	$142	-$142
1991	$610,952	$1,586	$609,366	$7,337	$2,277	$5,060	$44,331	$797	$43,534	$0	$142	-$142
1992	$548,896	$1,575	$547,321	$15,926	$3,542	$12,384	$42,944	$159	$42,785	$0	$142	-$142
1993	$655,894	$1,455	$654,439	$26,175	$3,745	$22,430	$44,169	$159	$44,010	$0	$142	-$142
1994	$640,427	$1,335	$639,092	$6,700	$3,770	$2,930	$42,213	$159	$42,054	$0	$142	-$142
1995	$618,012	$1,341	$616,671	-$12,363	$2,890	-$15,253	$34,046	$159	$33,887	$0	$142	-$142
1996	$731,344	$1,474	$729,870	-$5,514	$1,844	-$7,358	$35,623	$159	$35,464	$0	$142	-$142
1997	$922,792	$1,558	$921,234	$3,362	$1,925	$1,437	$38,239	$159	$38,080	$0	$142	-$142
1998	$778,133	$1,817	$776,316	$978	$1,787	-$809	$37,958	$159	$37,799	$0	$142	-$142
1999	$564,958	$1,979	$562,979	-$391	$1,616	-$2,007	$37,664	$159	$37,505	$41	$142	-$101
2000	$862,685	$2,045	$860,640	-$2,399	$1,452	-$3,851	$33,581	$159	$33,422	-$123	$142	-$265
2001	$1,454,710	$2,188	$1,452,522	-$2,202	$1,203	-$3,405	$35,559	$159	$35,400	$1	$150	-$149
2002	$1,454,567	$2,188	$1,452,379	$2,226	$1,040	$1,186	$37,844	$159	$37,685	$165	$150	$15
2003	$2,025,308	$2,188	$2,023,120	$2,489	$971	$1,518	$37,994	$159	$37,835	$291	$150	$141
2004	$2,497,349	$2,188	$2,495,161	$1,721	$953	$768	$39,428	$159	$39,269	$472	$120	$352

(continued)

Table 4-1. Net Benefits Attributable to DOE (thousands $2008), (continued)

	PDC			Binary			TOUGH			Cement		
Year	**Total Benefits**	**Program Expenses**	**Net Benefits**	**Total Benefits**	**Program Expenses**	**Net Benefits**	**Total Benefits**	**Program Expenses**	**Net Benefits**	**Total Benefits**	**Program Expenses**	**Net Benefits**
2005	$3,429,701	$2,188	$3,427,513	$6,471	$972	$5,499	$38,802	$159	$38,643	$1,540	$130	$1,410
2006	$4,631,182	$2,188	$4,628,994	$4,882	$972	$3,910	$38,797	$159	$38,638	$1,666	$150	$1,516
2007	$5,589,616	$2,188	$5,587,428	$2,677	$972	$1,705	$40,735	$159	$40,576	$1,811	$142	$1,669
2008	$6,081,340	$2,188	$6,079,152	$10,533	$972	$9,561	$41,817	$159	$41,658	$1,955	$142	$1,813
Undiscounted Total	$38,550,702	$63,178	$38,487,524	$124,206	$60,313	$63,893	$846,193	$15,455	$830,738	$7,820	$4,684	$3,136
PV[b] at 7%	**$7,813,212**	**$26,461**	**$7,786,751**	**$42,848**	**$26,819**	**$16,029**	**$219,445**	**$8,619**	**$210,826**	**$1,013**	**$1,938**	**-$925**
PV[b] at 3%	**$18,514,201**	**$41,015**	**$18,473,186**	**$76,269**	**$40,701**	**$35,568**	**$457,957**	**$11,655**	**$446,302**	**$3,199**	**$3,037**	**$162**
BCR at 7%	**295.3**			**1.6**			**25.5**			**0.5**		
BCR at 3%	**451.4**			**1.9**			**39.3**			**1.1**		
IRR	**139%**			**16%**			**48%**			**NA**		

[b] PV Base year is 1976.

4.1.1 Polycrystalline Diamond Compact Drill Bits

Technology Description: In the early 1970s, the Geothermal Division of DOE began research to produce an enhanced drill bit that would be more suitable than traditional drill bits for the high-density, high-temperature applications needed to drill geothermal wells (EERE/GTP, 2008a). This led to the development of several technological drilling advances, among which were PDC drill bits. A typical PDC drill bit consists of the drill bit body, usually made from steel or matrix metal, and drill bit cutters, their number varying with the bit diameter. PDC drill bits cutters are made from synthetic diamond powder (heated and pressurized graphite), cobalt, and tungsten carbide, and the bits have the key advantage of having no moving parts.

Next Best Alternative: PDC drill bit technology is an improvement to an existing technology. The next best alternative technology is the traditional moving parts roller cone bit. Roller cone bits are an established technology and continue to be used in applications involving shallow wells and softer rock formations. With its harder and longer lasting cutting surface, the PDC bit uses a simpler mechanical action, increasing productivity (feet drilled per hour) and efficiency (decreasing of the number of drill bits per well).

Benefits

Economic Benefits: Approximately 60% of worldwide oil and gas well footage in 2006 was drilled using PDC drill bits (Blankenship, 2009). The main advantage of PDC drill bits over conventional roller cone bits[2] is that they reduce frequency of pulling the drill string to replace the drill bit, allowing higher penetration rates and thus reducing the time (and cost) of renting expensive drill rigs. The use of PDC drill bits in offshore applications in the oil and gas industry is estimated to reduce costs by $58.54 per foot drilled, yielding a PV cost savings of $15.6 billion[3] from 1982 to 2008 (see Chapter 5 for calculations and citations for these numbers).

Environmental Benefits: Using PDC drill bits does not directly affect emissions. Environmental impacts were judged to be small and were not quantified.

Security Benefits: Using PDC drill bits reduces the cost and increases the availability of domestic oil and gas, which can reduce U.S. dependence on foreign imports of oil and gas. However, this potential impact was not quantified.

DOE Attribution: 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)

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[2] This is true in instances where PDC bits can be applied. PDC bits are less successful in high temperature hard and fractured rock formations. Since the principal wear mechanism of PDC drill bits is frictional heating, high temperatures only aggravate wear.

[3] Here and throughout the report, unless otherwise noted, PVs are discounted at 7%.

overcoming performance flaws and limitations, and (3) spurring the innovation that resulted in overall market success of PDC drill bits. As a result, based on the observable technology transfer, findings from published papers, and interviews, this study attributes 50% of the economic benefits from PDC bits to DOE. This attribution estimate is consistent with previous analysis (see Papadakis and Link [1997] and Falcone and Bjornstad [2005]). Thus, the PV of total benefits from DOE's contributions to developing drill bit technology equal $7.8 billion.

Measures of Economic Return: DOE program expenditures associated with PDC drill bit research are presented in Table 4-1 and total $26.5 million from 1982 to 2008. Comparing DOE's investment in PDC drill bit technology with benefits attributed to DOE yields a net benefit with PV of $7.8 billion ($18.5 billion discounted at 3%). The BCR is calculated to be 295.3 discounted at 7% (451.4 discounted at 3%), and the IRR for PDC drill bit technology project was 139%.

4.1.2 Binary Cycle Power Plant Technology

Technology Description: Binary cycle plants represented 14.5% of total geothermal capacity in the United States in 2008. Binary cycle geothermal power plant technology enables efficient use of lower temperature resources through the use of a closed loop heat transfer system. DOE assisted with the penetration of binary cycle plant technology in the United States, by sponsoring research to lower costs and by developing demonstration projects to showcase the technology's viability.

Next Best Alternative: The best alternative to binary cycle is usually flash cycle technology, which was used in 84% of geothermal power plants in 2008 (GEA, 2009a). However, the appropriate counterfactual technology for the benefits analysis differs depending on the temperature of the reservoir where binary cycle is installed:

- In reservoirs where the temperature range is 150°C to 190°C, flash cycle technology is economically viable but has lower electricity generation productivity as compared to binary cycle because of its lower conversion efficiency. Thus, in this temperature range, the next best alternative is a traditional, but less productive, flash cycle geothermal plant.
- In reservoirs where the temperature range is below 150°C, flash cycle technology is not economically viable and no other geothermal technology is available. Hence, for temperature ranges below 150°C, the next best alternative technology is generation from a mix of fossil fuels.

Benefits

Economic Benefits: Economic benefits include the market value of the additional electricity produced from reservoirs where the temperature range is 150°C to 190°C.[4] The PV of economic benefit is estimated to be approximately $109.9 million (discounted at 7%) from 1984 to 2008.

Environmental Benefits: Environmental benefits result from both (1) the additional renewable electricity generated from reservoirs where the temperature range is below 150°C, offsetting generation from a mix of fossil fuels and (2) the incremental renewable power generation (which has zero emissions) from reservoirs where the temperature range is 150°C to 190°C, which would have been flash cycle – degenerated electricity but are now binary cycle – generated electricity. The PV of environmental health benefits is estimated to be $127 million (discounted at 7%). In addition there are reductions of GHGs totaling 7.3 million tCO_2e from 1984 to 2008.

Security Benefits: Security benefits derive from reducing the probability and potential impact of oil and natural gas disruptions and price shocks or other energy system disruptions that would damage or disrupt the economy, environment, or national security of the United States. Table 4-2 presents the reduction in 4.9 billion cubic feet of natural gas or 862 thousand barrels of oil equivalent.

Table 4-2. Security Benefits of Binary Cycle Attributable to DOE, 1980-2008

Fossil Fuel	Binary Cycle
Natural gas (million cubic feet)	4,863
BOE (thousand barrels of oil equivalent)	861.8

DOE Attribution: The main impact of DOE on binary cycle technology has been the demonstration of commercial applicability of binary cycle technology and the provision of guaranteed loans, which helped industry to obtain financing. This accelerated the entry of the technology into the market. Interview participants estimated that the acceleration effect was less than five years but more than six months. Based on that estimate, it was assumed that the acceleration effect of DOE activities was two years. The PV of benefits attributable to DOE's acceleration effect equaled approximately $42.8 million (discounted at 7%).

Measures of Economic Return: DOE expenditures on binary cycle activities represent approximately 1.6% of EERE's total GTP budget from 1976 to 2008. The PV of expenditures (adjusted to 2008 dollars) equaled $26.8 million discounted at 7% ($40.7 million discounted at 3%). When expenditures are compared to the benefits with PV of $42.8 million discounted at 7% attributed to DOE, DOE's investment in binary cycle power plant technology yielded net benefits with the PV of $16.0 million

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[4] The increased productivity associated with binary cycle over flash at this temperature range is achieved at negligible incremental cost. Thus, the economic benefit is the value of the power generated. For the lower temperature range, because the cost of binary power generation is comparable to the cost of coal power generation there is no economic benefit, but there are environmental benefits.

discounted at 7% ($35.6 million discounted at 3%). The BCR discounted at 7% is calculated to be 1.6 (1.9 discounted at 3%), and the IRR for binary cycle plant technology is 16%.

4.1.3 TOUGH Series of Reservoir Models

Technology Description: Reservoir models simulate the flow of fluids and thermal energy in the subsurface. They are used as analytical and management tools in forecasting reservoir capacity, designing development activities, and identifying characteristics that may cause changes in the reservoir. Reservoir modeling helps optimize resources and manage risk. DOE's research efforts helped identify the limitations of traditional exploration techniques and demonstrate the potential for imaging and characterizing subsurfaces, which provided the foundation for geothermal reservoir modeling.

Next Best Alternative: Geothermal reservoir modeling, in general, is an example of new technology representing analysis capabilities of much higher complexity than previously available. Before capabilities for detailed computer simulation of geothermal reservoirs were developed, the best alternative was to use so-called "lumped parameter" models. These models simplified reservoir simulation and provided limited information about how fast this energy could be recovered, how many production and injection wells would be required, where these wells should be located, and at what rate makeup wells would be required as the reservoir was being depleted. This sometimes led to incorrect estimation of power plant capacity, thus increasing installed costs.

Benefits

The benefits associated with using reservoir modeling that were quantified for this study fall into two categories: (1) increased productivity of geothermal resources (the value of the additional electricity generated) and (2) the environmental health benefits associated with the additional renewable energy offsetting fossil fuel generation.

Economic benefits: Using reservoir modeling increased productivity of geothermal resources. These benefits are somewhat offset by additional exploration costs associated with reservoir modeling. However, in the aggregate, reservoir modeling has been profitable for the geothermal industry by improving subsurface exploration. The PV of total economic benefits of reservoir modeling from 1984 to 2008 equaled $503.3 million (discounted at 7%). In addition, reservoir modeling has been adapted for other uses, such as nuclear waste geologic storage, carbon dioxide (CO_2) sequestration, and remediation of subsurface contamination problems. For these applications, the TOUGH model has been the primary modeling tool; however, this study was not able to quantity the benefits of non-geothermal applications.

Environmental Benefits: The increased productivity of geothermal fields yields additional renewable energy that offsets generation from a mix of fossil fuels. The PV of the environmental health benefits associated with the additional renewable energy is estimated to be $450.8 million (discounted at 7%). In addition, there are reductions of GHGs totaling 22.9 million tCO_2e.

Security Benefits: Security benefits derive from reducing the probability and potential impact of oil and natural gas disruptions and price shocks or other energy system disruptions that would damage or disrupt the economy, environment, or national security of the United States. Table 4-3 presents the reduction in 19.4 billion cubic feet of natural gas or 3.4 million barrels of oil equivalent.

Table 4-3. Security Benefits of TOUGH Models Attributable to DOE, 1980-2008

Fossil Fuel	TOUGH Models
Natural gas (million cubic feet)	19,401
BOE (thousand barrels of oil equivalent)	3,438

DOE Attribution: DOE's activities in the late 1970s and early 1980s were at the forefront of geothermal reservoir model development, coinciding with the evolution of computer capabilities that enabled complex simulation models to be run cost effectively. To quantify attribution, this study partitioned the suite of available reservoir models into two groups: (1) the TOUGH series of models and (2) other reservoir models (e.g., TETRAD, STAR). Participants interviewed as part of this study indicated that the DOE attribution between the two groups is different:

- DOE had overwhelming influence (80%) on the TOUGH series models.
- DOE efforts were influential (20%) on other reservoir models.

Based on a study conducted by O'Sullivan (2001), the share of TOUGH usage for U.S. geothermal applications is approximately 5%, with other reservoir models accounting for 95% of U.S. geothermal reservoir modeling. Using these usage shares and the attribution rates, this study estimates that PV of total benefits discounted at 7% attributable to DOE equaled $219.4 million for the period 1980 to 2008.

Measures of Economic Return: The PV of DOE program expenditures, discounted at 7%, associated with the TOUGH family of reservoir models (adjusted to 2008 dollars) equaled $8.6 million from 1976 to 2008 ($11.7 million discounted at 3%). When compared with attributed benefits of $219.4 million discounted at 7%, DOE's investment in the TOUGH models yielded net benefits with PV of $210.8 million discounted at 7% ($446.3 million discounted at 3%). The BCR is calculated to be 25.5 discounted at 7% (39.3 discounted at 3%). The IRR for the TOUGH program is 48%.

4.1.4 High-Temperature Geothermal Well Cements

Technology Description: Early geothermal energy projects revealed that using Portland cement in geothermal wells was problematic, leading to frequent and costly repairs and significantly shorter well lifetimes. In the 1970s, DOE began supporting the development of new well cements that address these shortcomings through basic materials research and applied research on the cementitious properties of various chemical formulations. DOE's research led to the patenting and commercialization of a calcium aluminate phosphate (CaP) cement system that is resistant to acidic corrosion and maintains structural integrity at extremely high temperatures.

Next Best Alternative: High-temperature well cement is a technology improvement over existing Portland-based well cements commonly used in geothermal, oil, and gas wells. Originally developed for use in geothermal wells, high-temperature cement has also been used for enhanced oil recovery projects and offshore well drilling. The DOE-developed cement technology affects new well construction and ongoing maintenance at high-temperature geothermal production wells.

Benefits

Economic Benefit: The rapid deterioration of Portland cement in geothermal wells (<12 months) resulted in frequent well workovers and costly well remediation. The use of high-temperature cements enhances performance in terms of structural stability and corrosion resistance and is estimated to eliminate $150,000 in annual well remediation costs and extend the working life of geothermal production wells to 20 years or more. The economic benefits from high-temperature cements include (1) cost savings to the end users of CaP cement and (2) profits from the sale of ThermaLock cement. The PV of total benefits from the use of high-temperature cement from 1999 to 2008 is estimated to be $2.1 million (discounted at 7%), with the 99% of the benefits associated with cost savings to users.

Environmental Benefits: No environmental benefits were identified associated with using high-temperature cement. However, a complete life-cycle analysis including cement production (beyond the scope of this study) might identify emission reductions in GHGs and other pollutants.

Security Benefits: No security benefits were identified associated with using high-temperature cement.

DOE Attribution: DOE’s influence on the development of high-temperature cement varied over the 24-year period examined. For example, DOE had a very important influence on determining the direction of cement research, choosing to pursue a ceramic-based cement formulation over a more conventional Portland-based design. In contrast, since commercialization in 1999, Halliburton has marketed ThermaLock for use in domestic and international geothermal and enhanced oil recovery injection wells with minimal direct involvement from DOE. Averaging estimated influence factors over each stage in the technology development cycle yields an estimated 48.3% attribution rate. Thus, roughly half of the total benefits realized from the development CaP cement, or approximately $1 million, are directly attributable to GTP’s research and development activities.

Measures of Economic Return: PV of DOE program expenditures associated with cement materials research (adjusted to 2008 dollars) equaled $1.9 million (discounted at 7%) from 1976 to 2008 ($3 million discounted at 3%). Compared with the economic benefits attributed to DOE, DOE’s investment in CaP cement technology yielded PV of −$925 million discounted at 7% in net benefits ($162 million discounted at 3%). However, it is important to note that the technology is in its infancy, and experts interviewed for this analysis predict a considerable increase in the rate of adoption over the next 5 years. Allowing more time for industry to adopt the existing CaP cement technology in geothermal wells would significantly increase the total economic benefits realized and alter the results of this analysis. Depending on the rate of adoption, economic benefits may potentially exceed the total development costs, yielding a positive return to program costs in the near term.

4.2 Benefit-Cost Analysis for GTP

The analysis of economic, health, and knowledge benefits is summarized in this section, and additional detail is provided in Chapters 5 through 8.

4.2.1 Quantified Economic and Environmental Health Benefits

The four technologies selected for analysis in this study reflect the wide range of research activities conducted by GTP and, as a group, have generated significant economic and environmental benefits. Table 4-4 shows the aggregate monetized benefits for the four technologies and partitions them into general categories. Cost reductions in drilling and exploration accounted for the majority of the quantified benefits with PV of $7.8billion discounted at 7%. PV of increased operating efficiency and productivity accounted for $135.6 million discounted at 7% and environmental health impacts accounted for $126.6 million discounted at 7%.

Table 4-4. Summary of GTP Benefits, 1976–2008 (thousands $2008)

Benefits	Total Benefits PV[a] at 7%
Cost reduction in drilling and exploration	$7,814,225
Increased operating efficiency and productivity	$135,649
Environmental health impacts	$126,644
Total benefits attributable to GTP	$8,076,518

[a] PV base year is 1976.

In addition, as shown in Table 4-5, research activities associated with these four technologies accounted for only 3.8% of GTP's budget from 1976 to 2008 (based on cost data discounted at 7%). Hence, it is very likely that the total benefits associated with GTP activities greatly exceed the $8.1 billion quantified. However, it is still informative to compare the benefits from the four technologies to the total GTP expenditures to obtain lower bound measures of economic return.

Table 4-5. Summary of GTP Expenditures, 1976–2008

Technologies	Program Expenses PV[a] at 7% (thousands $2008)	Percentage of Total
PDC drill bits	$26,463	1.6%
High-temperature cement	$1,934	0.1%
TOUGH Models	$8,620	0.5%
Binary cycle plants	$26,819	1.6%
Total of four technologies	$63,836	3.8%
Total GTP expenditures	$1,660,194	100.0%

[a] PV base year is 1976.

Table 4-6 presents the cluster analysis results for GTP. PV of net benefits (in 2008 dollars) for the program is $6.4 billion discounted at 7% ($17 billion discounted at 3%). The BCR is 4.9 discounted at 7% (9.1 discounted at 3%). The IRR is 22%.

Table 4-6. Benefit-Cost Analysis for GTP, 1976–2008 (thousands $2008)

Geothermal Program			
Year	**Total Benefits**	**Program Expenses[a]**	**Net Benefits**
1976	$0	$92,819	-$92,819
1977	$0	$130,899	-$130,899
1978	$0	$288,654	-$288,654
1979	$0	$367,328	-$367,328
1980	-$3,158	$316,935	-$320,093
1981	$7,041	$324,090	-$317,049
1982	$323,318	$142,327	$180,991
1983	$394,536	$93,412	$301,124
1984	$642,756	$41,677	$601,079
1985	$670,808	$57,793	$613,015
1986	$468,656	$45,668	$422,988
1987	$480,161	$34,891	$445,270
1988	$493,391	$35,623	$457,768
1989	$502,671	$30,829	$471,842
1990	$672,701	$26,832	$645,869
1991	$662,620	$43,236	$619,384
1992	$607,766	$38,143	$569,623
1993	$726,238	$31,619	$694,619
1994	$689,340	$31,251	$658,089
1995	$639,695	$50,360	$589,335
1996	$761,452	$38,384	$723,068
1997	$964,393	$37,373	$927,020
1998	$817,069	$36,402	$780,667
1999	$602,273	$35,194	$567,079
2000	$893,744	$28,554	$865,190
2001	$1,488,069	$32,205	$1,455,864
2002	$1,494,803	$32,149	$1,462,654
2003	$2,066,083	$30,550	$2,035,533
2004	$2,538,971	$29,348	$2,509,623
2005	$3,476,513	$27,414	$3,449,099
2006	$4,676,527	$24,478	$4,652,049
2007	$5,634,838	$5,107	$5,629,731
2008	$6,135,647	$19,307	$6,116,340
Undiscounted Total	$39,528,921	$2,600,851	$36,928,070
PV[b] at 7%	**$8,076,518**	**$1,660,194**	**$6,416,324**
PV[b] at 3%	**$19,051,625**	**$2,082,623**	**$16,969,002**
BCR at 7%			**4.9**
BCR at 3%			**9.1**
IRR			**22%**

[a] Source: U.S. DOE (2008b).

[b] Base year is 1976, which is the first year of DOE program expenses.

It should be noted that additional benefits are associated with the four technologies that could not be quantified given this study's timing and resources. For example, environmental health benefits only capture the impact of reducing emissions of particulate matter, nitrous oxides, and sulfur oxides and do not reflect other environmental health benefits associated with reductions of other pollutants (such as CO_2, mercury).

In addition, the use of renewable energy systems, such as geothermal, to generate electricity would also have an impact on fresh water resources in the United States. Thermoelectric generation requires significant amounts of water for cooling and emissions scrubbing. Power plants account for approximately 40% of fresh water withdrawals. Available surface water supplies have not increased in 20 years, and many underground water tables are dropping at an unsustainable rate.

4.2.2 Knowledge Benefits

Principal conclusions from assessing knowledge benefits resulting from GTP-funded R&D are the following: the resulting knowledge base includes, among other things, approximately 90 DOE-attributed patent families (where each family contains all patents based on the same invention) and more than 3,000 publications. These patents and publications provided a noteworthy foundation for further innovation in the geothermal energy industry and also in the gas and oil industries. 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 research.

- Of a total population of more than 1,000 geothermal patent families assigned to numerous organizations, 21% were linked to earlier DOE-attributed geothermal patents and publications, second only to that for the patent portfolio of Chevron, which is billed as the world's largest producer of geothermal energy. Furthermore, greater than 40% of Chevron's patents have also built extensively on earlier DOE-attributed geothermal patents and papers, as well as high percentages of the patent portfolios of Ormat and other leading companies in geothermal energy.
- Among the DOE-attributed patent families and publications are those describing Organic Rankine and Kalina thermodynamic cycles, the generation of geothermal energy from hot dry rocks, techniques for treating geothermal brine, advanced drill bits, downhole electronics and data transmission, improved cements to withstand conditions in wells, and other innovations describing geothermal power plants and power generation.

In addition to the knowledge base captured in patents, papers, models, prototypes, test data, and other tacit forms of knowledge, DOE-funded research has trained technologists and researchers in geothermal research across the nation and fostered the development of a network among them.

4.3 Sensitivity Analysis

When estimating the environmental health benefits, it was assumed that in the absence of geothermal electricity, additional coal-, natural gas-, and oil-fired power plants would have been built to meet electricity demand. Appendix C describes the method used to obtain the appropriate fuel mix for each state that geothermal power likely offsets (the average value of this mix across states is 60% coal, 39% natural gas, and 1% oil). To investigate how sensitive our findings are to this calculation approach, this study estimated environmental health benefits using an alternative scenario of 50% coal and 50% natural gas, the results of which are presented in Table 4-7. The alternative scenario is not based on new information but is simply intended to illustrate how environmental benefits change as the fuel mix offset changes.

Table 4-7. Environmental Benefits Attributed to DOE: Sensitivity to Displaced Fuel Type

	Displaced Generation		**Percentage Reduction**
	60% Coal, 39% NG, 1% Oil[1]	**50% Coal, 50% NG**	
PM (short tons)	22,194	18,780	15.4%
SO_2 (short tons)	9,611	7,992	16.9%
NO_X (short tons)	5,035	4,227	16.0%
GHG (million tCO_2e)	6,585	6,268	4.8%
Monetized health benefit (PV[a] at 7%, thousands $2008)	$126,644	$107,501	15.1%

[a] PV base year is 1976.

Because natural gas generates significantly less PM than coal and PM is the main driver of health impacts in the COBRA model, decreasing the share of coal generation from 60% to 50% decreases the environmental health benefits attributed to DOE by 15.1% or $19.1 million. However, because the majority of benefits are attributable to PDC drill bits, this change reduces the BCR for the cluster analysis by only 0.01 from 4.70 to 4.69.

The costs for TOUGH series of models and CaP cement technologies were estimated based on FTE estimates or DOE internal cost records; however, this information was not available for binary cycle plants and PDC drill bit technologies. The costs for the two latter technologies were estimated based on relevant line items from overall GTP budget. A portion of line item expenses from the GTP budget was assigned to these two technologies. This approach likely overestimated PDC drill bit and binary cycle plant technology costs. To investigate how sensitive our findings are to this approach, this study lowered PDC drill bit and binary cycle plants technology costs by 50%. The resulting benefit-cost ratios are presented in Table 4-8. This alternative scenario is not based on specific information but is presented to illustrate how PDC drill bit and binary cycle plant technology and overall benefit-cost ratios change when the cost calculation approach is changed.

Table 4-8. Sensitivity Analysis of GTP Technology Case Study Costs

Technology	**Benefit-Cost Ratio at 7% (4 Case Study Technology Costs/4 Case Study Technology Benefits)**	
	Baseline	**Decrease PDC and Binary Costs by 50%**
PDC drill bits	295.3	590.5
Binary Cycle	1.6	3.2
TOUGH Models	25.5	25.5
High-temperature cement	0.5	0.5
4 Case Study Technologies	126.5	217.1

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[1] This represents the average of fossil fuel mix offset by geothermal production in each state. See Appendix C for details.

4.4 Caveats

4.4.1 Oil and Gas Sector Benefits

The majority of GTP benefits quantified as part of this study are attributed to PDC drill bits. These benefits were primarily in the form of cost reductions in exploration and drilling of oil and gas. Although this category of benefits is not the main objective of GTP's R&D, this category does reflect economic benefits that are realized by society. It is not uncommon for, spillover benefits to account for a significant share of societal benefits from government-sponsored R&D programs (see Chapter 9 for additional discussion of knowledge benefits).

However, it is also possible that knowledge spillovers could have negative benefits from a societal perspective. For example, if cost reductions lead to the increased production of a less desirable good, this could result in a decrease in social welfare. In terms of this study, if the use of PDC drill bits lowers the cost of gasoline and natural gas products, this could increase their use, which carries the negative externalities discussed in earlier sections. The extent of this phenomenon depends on how prices are set in the energy markets and on the demand elasticity of final consumers. Although an analysis of this potential impact is beyond the scope of this study, the following points are noted:

- Energy prices for crude oil and natural gas are driven in large part by output decisions of producing countries and political unrest and minimally by exploration and development costs.
- Final consumers have historically been shown to be price inelastic with respect to their gasoline and natural gas consumption.

As a result, the occurrence of increased use of fossil fuels due to PDC drill bit cost reductions is likely to be minor.

5. POLYCRYSTALLINE DIAMOND COMPACT DRILL BITS: TECHNOLOGY IMPACT ASSESSMENT

5.1 Introduction

Approximately 60% of worldwide oil and gas well footage in 2006 was drilled using polycrystalline diamond (PDC) drill bits. A typical PDC compact drill bit consists of the drill bit body, usually made from steel or matrix metal, with synthetic diamond (PDC) cutters attached. Figure 5-1 compares typical PDC drill bits to roller-cone drill bits. DOE initially sponsored PDC drill bits as a potential application for geothermal wells and they have since been widely adopted by the oil and gas industry. This section discusses the history and social benefits of PDC drill bit technology attributable to DOE, and DOE's role in bringing this technology to the U.S. market. PV of total benefits related to PDC drill bit technology are estimated to be approximately $15 billion (discounted at 7%). Approximately $7.6 billion (discounted at 7%) of these benefits can be attributed to DOE through its research activities resulting from an investment with PV of $26.5 million discounted at 7%.

Figure 5-1. PDC and Roller-Cone Drill Bits

PDC Drill Bits **Roller-Cone Drill Bits**

Source: EERE/GTP (2008c)

5.2 History of the Technology

In the early 1970s, the Organization of the Petroleum Exporting Countries (OPEC) and individual oil-producing countries instituted higher prices and oil embargoes from 1973 to 1985, putting pressure on the U.S. oil companies to expand oil production to more challenging geographic regions, such as deeper wells in the Gulf of Mexico (Jones, 1988) and to look for other energy sources. These events led to the development of several technological drilling advances, among which was the PDC drill bit. At that time, government labs began research to produce an enhanced drill bit that would reduce drilling costs for geothermal wells. Drilling is a large part of the capital cost of a geothermal power plant; thus, cheaper drilling provides a definite stimulus for placing geothermal power online.

High temperatures in geothermal wells cause serious damage to traditional roller cone bits, partly because of damage to the bearing seals and bearings. PDC drill bits have the advantage of no moving parts. A typical PDC drill bit consists of the drill bit body, usually made from steel or matrix metal (Mensa-Wilmot, 2003), with PDC cutters attached. The number of cutters varies with the bit diameter and the hardness of the formation that it is designed to drill. The cutters are made under immense pressure and temperature from synthetic diamond powder sintered with cobalt onto a tungsten carbide substrate. The resulting disks (also known as compacts) can be made in different sizes but are typically 0.5 inch in diameter and 0.3 inches thick. The disks are bonded to tungsten carbide cylinders to form cutters, and the cylinders are then brazed into the bit body (Falcone and Bjornstad, 2005).

General Electric (GE) developed synthetic diamonds in 1955 and first used them on prototype drill bits in the field in 1973 (Madigan and Caldwell, 1981). However, field versions of early bits were disappointing, because the compacts detached from their mounts and wore out quickly. To address these issues, beginning in the 1970s, Sandia National Laboratories (SNL) conducted in-house research and promoted industry research and development by funding field tests and fundamental studies of rock-cutting interactions and frictional heating of the cutters. The research was broadly focused on the following areas (Finger and Glowka, 1989):

- Bit-rock interaction to understand how cutters induce failure in rock.
- Diffusion bonding to prevent cutters from detaching from the mounting studs or the bit body.
- Cutter temperature modeling to understand how frictional heating affects the wear behavior of PDC cutters.
- Single-cutter tests to model bit behavior as a function of a combination of parameters, such as vertical force, depth of cut, type of rock, rake angle, and lubricity of the drilling fluid.
- Bit design modeling to determine the layout of cutter patterns on a PDC.

The first commercial application of PDC drill bits occurred in 1976, and in 1977, GE marketed the first PDC cutter under the name Stratapax (Slack and Wood, 1982). PDC bits were initially less successful in geothermal formations because the principal wear mechanism of PDC drill bits is frictional heating. High-heat and hard and fractured rock formations aggravated that problem. Nonetheless, PDC bits drill soft formations at high temperatures. Successful PDC drill bit research was adopted by the oil and gas industry.

Cooperation between the oil and gas industry and SNL began during the period 1973 to 1977, while the lab was working with GE on improving the performance of the PDC drill bit. SNL sponsored wear and friction tests and conducted research on drill mechanics and hydraulics. After drill bit commercialization in 1977, Sandia kept working with the industry (because it was willing to participate in research that was mutually beneficial to the geothermal program and oil and gas industry), and the R&D program continued (Papadakis and Link, 1997). SNL helped resolve several technical problems exhibited by PDC bits and aided in bit design. Sandia National Laboratories' computer program, STRATAPAX, released in 1982, and later PDCWEAR, released in 1986, helped manufacturers place cutters on the bit strategically (Falcone and Bjornstad 2005). PDCWEAR could “compare bit designs and gain detailed information on the individual cutters so that the bit design can optimally place the cutters to produce uniform cutter wear. PDCWEAR also predicted the performance of specific bit-rock combinations” (Finger and Glowka, 1989, p. 63).

SNL’s PDC R&D program ran through 1986. After this, SNL’s scientists and engineers continued to contract with a consortium of PDC drill bit manufacturers and university researchers to work on advancing the PDC technology (Glowka and Schaefer, 1993). For example, in 1995, Sandia’s scientists collaborated with five drill bit companies (in the research sponsored by the industry) to improve performance of PDC drill bits in harder rock formations (Glowka et al., 1995) and in 2004 SNL cooperated with bit manufacturers in testing “best effort” drag bits in extensive drilling tests (Wise et al., 2004).

In general, advances in PDC drill bit technology since the first commercial application can be broken into three overlapping time segments:

- From 1977 to 1986, fundamental design and manufacturing deficiencies were identified and corrected.
- From 1979 to 1998, enabling research in bit mechanics, hydraulics, and thermal effects was performed. The PDCWEAR computer code was developed, which enabled the development of anti-whirl drill bits. Also, best practices in operation were established during this period.
- From 1996 to 2006, drilling dynamics were addressed, and improved cutter structures were tested and implemented. Integrated bit/bottom hole assembly was developed, and rotary steerable subs were introduced (Blankenship, 2009).[1]

Experts and practitioners agree that Sandia National Laboratories played an important role in developing PDC drill bit technology. The lab’s contribution to PDC technology included providing financing and R&D contracts to GE to run wear and friction tests, performing internal research on PDC drill mechanics and hydraulics, performing PDC drill bit tests in the field, and resolving technical problems with PDC drill bits (Papadakis and Link, 1997). The transfer of knowledge from DOE to drill bit manufacturers occurred through peer-to-peer discussion and numerous presentations and papers published by SNL.

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[1] Note that our economic benefit estimates below are based on per linear foot drilled and hence capture impacts for both horizontal and vertical drilling.

5.3 Next Best Alternative

Polycrystalline diamond compact drill bit technology is an example of improvement to an existing technology. The next best alternative technology is the traditional moving parts roller cone bit.[1] Roller cone bits are an established technology and continue to be used in applications where PDC bits are unsuitable, such as very hard formations. With its harder and longer lasting cutting surface, the PDC bit uses a more efficient mechanical action, shearing rock instead of crushing it.

This mechanical action increases productivity (feet drilled per hour) and reduces the frequency of pulling the drill string to exchange a drill bit; thus, increasing efficiency (decreasing of the number of drill bits per well). Compared to roller cone drill bits, PDC drill bits reduce the time and costs of drilling. Both PDC and roller cone drill bits have improved over time. However, there is limited empirical data to measure improvements in cost effectiveness of both drill bit types. Thus, this study uses fixed “delta” technical impact metrics over the time period of this analysis. This assumes that improvements over the technology’s lifespan are comparable for both the PDC and the alternative roller cone drill bits.

5.4 Benefits Calculations

Benefits realized from using PDC drill bit technology are primarily economic benefits and are segmented into profits to manufacturers of PDC drill bits and cost reductions to oil producers from using PDC drill bits in oil exploration. Table 5-1 summarizes the key parameters and assumptions used to estimate benefits.

Table 5-1. Key Parameters and Assumptions Used in the PDC Drill Bit Benefits Analysis

Parameters/Assumptions	Source
PDC drill bit market penetration 60% by 2008	Blankenship (2009)
Crude oil and natural gas exploratory and developmental well footage drilled	Crude Oil Developmental and Exploratory Well Footage (U.S. DOE, 2010a); Natural Gas Developmental and Exploratory Well Footage (U.S. DOE, 2010b)
PDC drill bits yield a cost reduction of $59 per foot drilled	Average of seven empirical studies published between 1982 and 1997
6.5% net profit estimate for drill bit producers	Falcone and Bjornstad (2005)
50% attribution of benefits to DOE	Published literature including Papadakis and Link (1997), interviews with industry and DOE experts

5.4.1 Economic Benefits (Profits) to PDC Drill Bit Producers

To estimate the benefits to polycrystalline diamond compact drill bit producers, historical PDC drill bit sales were studied, starting in 1982, which was the first year for which the PDC market could be defined (Falcone and Bjornstad, 2005). This study used data from three sources to construct sales estimates from 1982 to 2008: Falcone and Bjornstad (2005) provided sales estimates for 1982 to 1992, the U.S. DOE

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[1] PDC drill bits replaced roller cone bits for certain applications in the oil and gas industry; however, roller cone bits are still used almost exclusively for geothermal applications.

(2000a) provided sales estimates for 2000, and Freedonia Group (2009) supplied sales estimates for 2007. Sales for 1993 to 1999 and 2001 to 2008 were calculated from the above data using linear interpolation. The estimated sales for the entire period are presented in Table 5-2.

We considered profit margins for the four largest PDC drill bit manufacturers: Baker Hughes, Smith Bits, ReedHycalog, and Security-DBS. Unfortunately, all four top producers are subsidiaries of large oil (service or tool and equipment) companies: Baker Hughes of Baker International, Smith Bits of Smith International, Security-DBS of Halliburton, and ReedHycalog of National Oilwell Varco. Parent companies did not provide profitability numbers for subsidiaries, and using parent company profitability information would be misleading. Falcone and Bjornstad (2005) estimated 6.5% as a net profit estimate for drill bit producers. Therefore, 6.5% was used as a net profit estimate for drilling companies. The profit calculation for drill bit manufacturers is presented in Table 5-2.

Table 5-2. Profits to PDC Drill Bit Manufacturers from PDC Drill Bit Technology, 1982–2009

Year	Annual Sales of PDC Drill Bits (thousands $current)	Annual Sales of PDC Drill Bits (thousands $2008)	Profits[a] (thousands $2008)
1982	$300,697	$588,679	$38,264
1983	$377,503	$710,928	$46,210
1984	$595,101	$1,080,234	$70,215
1985	$626,449	$1,103,680	$71,739
1986	$413,769	$713,149	$46,355
1987	$420,911	$705,044	$45,828
1988	$450,533	$729,608	$47,425
1989	$443,303	$691,796	$44,967
1990	$590,329	$886,913	$57,649
1991	$583,451	$846,563	$55,027
1992	$524,734	$743,776	$48,345
1993	$627,620	$870,365	$56,574
1994	$613,365	$833,037	$54,147
1995	$592,408	$788,196	$51,233
1996	$701,587	$916,030	$59,542
1997	$885,875	$1,136,466	$73,870
1998	$747,337	$948,036	$61,622
1999	$542,911	$678,724	$44,117
2000	$829,704	$1,015,301	$65,995
2001	$1,400,276	$1,675,773	$108,925
2002	$1,400,979	$1,649,763	$107,235
2003	$1,952,203	$2,250,638	$146,291
2004	$2,409,614	$2,701,058	$175,569
2005	$3,312,964	$3,594,016	$233,611
2006	$4,478,373	$4,704,668	$305,803
2007	$5,410,144	$5,525,630	$359,166
2008	$5,890,035	$5,890,035	$382,852
Undiscounted Total			$2,858,577
PV[b] at 7%			$602,767

Sources: Falcone and Bjornstad (2005), U.S. DOE (2000a), Freedonia Group (2009).

[a] Calculations are based on assumption of 6.5% profit margin.

[b] Base year is 1976, which is the first year of DOE program expenses.

5.4.2 Economic Benefits (Cost Reductions) from Using PDC Drill Bits

One of the main expenditures to oil production companies is the cost of renting drilling rigs. Regardless of whether the well is successful, drilling companies could pay up to $1,000,000 (in 2008 dollars) for a drilling rig per day (Falcone and Bjornstad, 2005; Blankenship, 2009). Oil producers often use cost per foot calculations as a measure of drilling efficiency. The following formula is used to calculate cost per foot:

$$\frac{\text{Cost}}{\text{Foot}} = \frac{[(\text{Drilling Time} + \text{Trip Time}) \times \text{Hour Rig Cost} + \text{Bit Cost} + \text{Tool Cost} + \text{Labor Cost}]}{\text{Footage Drilled}}$$

The main advantage of PDC drill bits over the conventional roller cone bits is that they allow higher penetration rates and reduce the frequency of changing the drill bit, reducing the time of renting expensive drill rigs. Even though PDC bits themselves cost more than roller cone bits, they produce net benefits of cost per foot. To calculate the benefits to the oil extraction industry resulting from cost savings of drilling with PDC bits, this study uses the following formula:

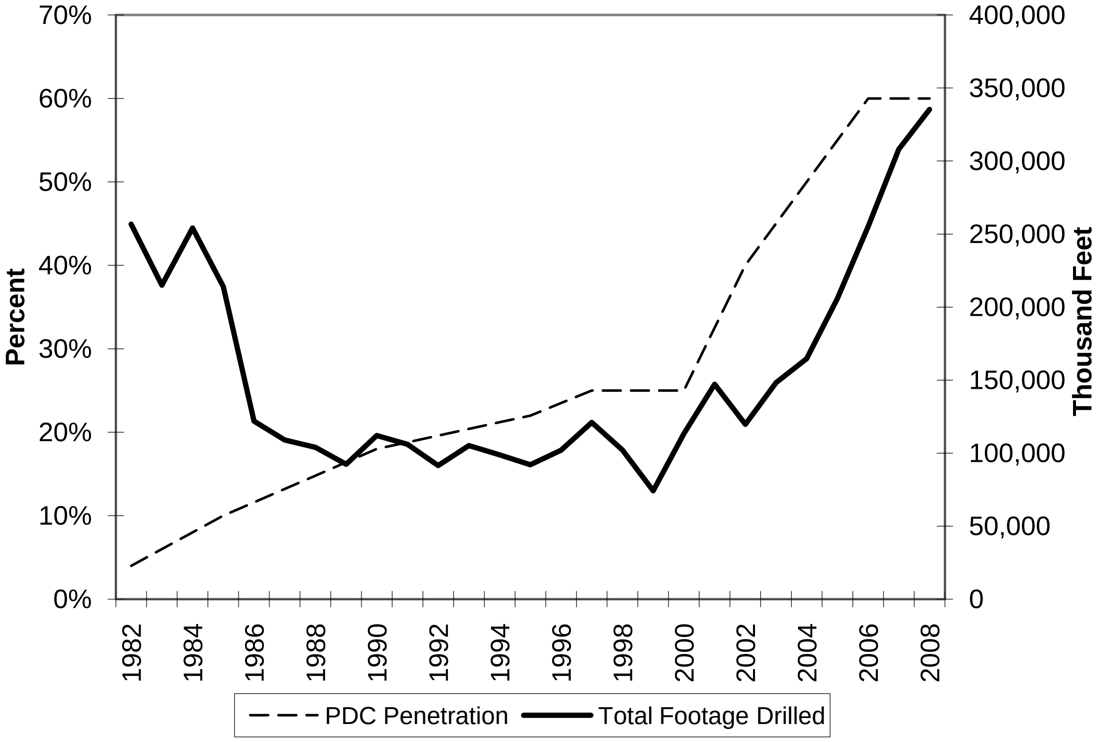
$$\begin{aligned}\text{Cost Savings} = {} & (\text{PDC Market Penetration}) \text{ x } (\text{Annual Oil and Gas Well Footage Drilled}) \\ & \text{x } (\text{Savings - Per - Foot})\end{aligned}$$

Where:

- PDC market penetration is the percentage of crude oil and gas wells drilled with PDC bits,
- Annual well footage drilled is the oil well footage drilled in the United States annually, and
- Savings-per-foot is the inflation-adjusted dollars saved per foot from drilling wells with PDC bits as compared to baseline roller cone bits.

Figure 5-2 presents the percentage of world oil and gas well footage drilled with PDC drill bits. This study assumes that drilling in the United States followed a similar pattern. Market penetration started low in early 1980s and grew greatly in the 1990s with greater use of horizontal drilling and an increase in oil and gas demand.

Figure 5-2. PDC Drill Bits' Penetration Curve and Total Worldwide Crude Oil and Natural Gas Well Footage Drilled with PDC Bits, 1982–2008



Source: Blankenship (2009).

Figure 5-2 also presents total developmental oil and gas well footage drilled in the United States from 1982 (the year PDC drill bits were introduced to the market) to 2008. Since the oil boom of the early 1980s, there has been a significant decline in the total footage drilled; however, the total footage drilled started rising in the early 2000s and reached 350 million feet in 2008.

Table 5-3 presents the calculation of average savings per foot from drilling oil wells with PDC drill bits as compared with conventional roller cone bits. Seven studies were located that presented savings-per-foot estimates, dating from 1982 to 1997. These studies represent four geographic locations and presented a total of 19 savings estimates for seven different hole sizes for both oil and gas wells. Savings estimates were adjusted by the gross domestic product deflator, and weighted by the length drilled. The average cost saving was $58.54 per foot in 2008 dollars.

Table 5-3. Average Cost Reductions per Foot in Crude Oil and Natural Gas Wells Drilled with PDC Bits

Study (Year)	Year Sampled	Area	Hole Diameter (in)	Length Drilled (feet)	Real Savings per foot drilled ($2008)	Weighted Savings per foot drilled ($2008)
Slack and Wood (1982)	1981	Texas	8 3/4	1,700	$20	$0.68
	1981	Texas	8 3/4	731	$288	$4.21
	1981	Texas	8 3/4	800	$309	$4.94
	1981	Texas	8 3/4	3,412	$13	$0.90
	1981	Texas	8 3/4	4,590	$47	$4.31
	1981	Texas	8 1/2	1,782	$180	$6.41
	1981	Louisiana	8 1/2	3,860	$12	$0.93
	1981	Louisiana	6 3/4	4,113	$11	$0.91
Gani (1982)	1982	Indonesia	12 1/4	3,491	$35	$2.44
	1982	Indonesia	7 3/8	705	$192	$2.70
	1982	Indonesia	7 3/8	507	$80	$0.81
Wampler and Myhre (1990)	1990	South Texas	8 3/4	3,000	$9	$0.54
	1990	South Texas	8 3/4	1,300	$6	$0.16
	1990	South Texas	6 1/4	2,100	$7	$0.29
Boudreaux and Massey (1994)	1994	Gulf of Mexico	12 1/4	2,841	$69	$3.91
Casto (1995)	1995	Gulf of Mexico	12 1/4	2,841	$187	$10.61
McDonald and Felderhoff (1996)	1996	Gulf of Mexico	6 1/8	2,701	$22	$1.19
Mensa-Wilmot (1997)	1997	Gulf of Mexico	12 1/4	5,814	$43	$5.00
	1997	Gulf of Mexico	12 1/4	3,767	$101	$7.60
Average					**$86**	**$58.54**

Crude oil and gas well footage drilled with PDC drill bits (see Table 5-4) were calculated based on information from Figure 5-2. This footage was multiplied by cost reduction of $59 per foot to obtain annual benefits to the oil and gas extraction industry. The PV of total benefits equaled approximately $15 billion (discounted at 7%).

Table 5-4. Benefits from Using PDC Drill Bit Technology

Year	Crude Oil and Natural Gas Exploratory and Developmental Well Footage Drilled with PDC Bits[a] (thousand feet)	Savings Based on Well Footage[b] (thousands $2008)
1982	10,273	$601,381
1983	12,897	$754,990
1984	20,331	$1,190,177
1985	21,402	$1,252,873
1986	14,136	$827,521
1987	14,380	$841,805
1988	15,392	$901,048
1989	15,145	$886,588
1990	20,168	$1,180,635
1991	19,933	$1,166,878
1992	17,927	$1,049,447
1993	21,442	$1,255,215
1994	20,955	$1,226,706
1995	20,239	$1,184,791
1996	23,969	$1,403,145
1997	30,265	$1,771,713
1998	25,532	$1,494,643
1999	18,548	$1,085,800
2000	28,346	$1,659,375
2001	47,839	$2,800,495
2002	47,863	$2,801,900
2003	66,695	$3,904,325
2004	82,322	$4,819,130
2005	113,184	$6,625,791
2006	152,999	$8,956,561
2007	184,832	$10,820,065
2008	201,227	$11,779,829
Undiscounted Total		$74,242,828
PV[c] at 7%		**$14,981,464**

Source: Crude Oil Developmental and Exploratory Well Footage (U.S. DOE, 2010a); Natural Gas Developmental and Exploratory Well Footage (U.S. DOE, 2010b)

[a] Crude Oil and Natural Gas Exploratory and Developmental Well Footage Drilled with PDC Bits = (Oil Well Footage + Gas Well Footage) x Penetration Curve (from Figure 5-2).

[b] Savings Based on Wells Footage = Crude Oil and Natural Gas Exploratory and Developmental Well Footage Drilled with PDC Bits x Average Cost Reductions per Foot in Crude Oil and Natural Gas Wells Drilled with PDC Bits ($58.54 from Table 5-2).

[c] Base year is 1976, which is the first year of DOE program expenses.

Calculations of total benefits of PDC drill bit technology are presented in Table 5-5. Total benefits represent the sum of cost reductions to oil and gas producers and profit to PDC drill bit manufacturers. For 1982 to 2008, the introduction of PDC drill bit technology resulted in total benefits with PV of $15.6 billion (discounted at 7%).

Table 5-5. Total Economic Benefits from PDC Drill Bit Technology (thousands $2008)

Year	Savings Based on Well Footage	Annual Profits from Sales of PDC Drill Bits	Total Benefit
1982	$601,381	$38,264	$639,646
1983	$754,990	$46,210	$801,201
1984	$1,190,177	$70,215	$1,260,392
1985	$1,252,873	$71,739	$1,324,612
1986	$827,521	$46,355	$873,876
1987	$841,805	$45,828	$887,633
1988	$901,048	$47,425	$948,472
1989	$886,588	$44,967	$931,555
1990	$1,180,635	$57,649	$1,238,284
1991	$1,166,878	$55,027	$1,221,904
1992	$1,049,447	$48,345	$1,097,792
1993	$1,255,215	$56,574	$1,311,788
1994	$1,226,706	$54,147	$1,280,853
1995	$1,184,791	$51,233	$1,236,024
1996	$1,403,145	$59,542	$1,462,687
1997	$1,771,713	$73,870	$1,845,583
1998	$1,494,643	$61,622	$1,556,266
1999	$1,085,800	$44,117	$1,129,917
2000	$1,659,375	$65,995	$1,725,369
2001	$2,800,495	$108,925	$2,909,420
2002	$2,801,900	$107,235	$2,909,135
2003	$3,904,325	$146,291	$4,050,617
2004	$4,819,130	$175,569	$4,994,699
2005	$6,625,791	$233,611	$6,859,402
2006	$8,956,561	$305,803	$9,262,365
2007	$10,820,065	$359,166	$11,179,231
2008	$11,779,829	$382,852	$12,162,681
Undiscounted Total	$74,242,828	$2,858,577	$77,101,405
PV[a] at 7%			**$15,626,424**

[a] Base year is 1976, which is the first year of DOE program expenses.

5.4.3 Environmental Benefits

The development of polycrystalline diamond compact drill bits was one of several technological advances which in combination supported the introduction of directional drilling. Through the use of horizontal drilling, the physical foot print of drilling platforms has been reduced, resulting in less disruption of the environment. Because it would be difficult to quantify this impact it was not included in the monetary benefits estimates.

5.4.4 Security Benefits

The use of PDC drill bits lowered the cost of oil and gas production and potentially increased domestic supply. This may have had an effect on the U.S. dependence on foreign oil and gas imports. However, quantifying these impacts was beyond the scope of this study.

5.5 Attribution Share

Sandia National Laboratories played a critical role in the development and adoption of the PDC drill bit technology. Through a review of the literature and interviews with experts, this study found that SNL significantly contributed to the development and adoption of PDC technology by (1) developing the bit and getting it to the market, (2) overcoming many of the performance flaws and limitations, and (3) spurring the innovation that resulted in overall market success of PDC drill bits. Table 5-6 provides an overview of SNL's contributions at the different stages of the PDC bit development life cycle.

SNL conducted research on bit mechanics and hydraulics which would prove useful in overcoming some of the technologies' limitations. The Lab's research identified the cause of and provided a solution to catastrophic bit failure, and solved the bit's spalling (or chipping off of diamond cutter) problem, resulting in solutions that became industry standards. To resolve the spalling problem, an issue caused by wear rate, SNL established an optimal bit parameter (a 20-degree back-rake angle) and designed a nozzle layout to achieve optimal cooling of the bit. Both of those innovations were adopted and widely used by bit manufacturers. SNL also created sophisticated computer code that allowed manufacturers position the desired number of cutters on a bit (Falcone and Bjornstad, 2005).

SNL's R&D efforts, publications, and innovations brought attention and publicity to PDC drill bit technology, resulting in its overall market success. As mentioned previously, GE acknowledged that SNL's research helped deliver PDC drill bits to the market on time. Many officials credited the "publicness" of Sandia's efforts as a difference maker in PDC drill bit success (Papadakis and Link, 1997). SNL's research resulted in 34 published journal articles and 42 presentations, representing the flow of information from SNL to the industry. Moreover, approximately half of the industry used one of the versions of SNL's computer code.

Furthermore, using PDCWEAR code as a basis, Amoco developed an anti-whirl drill bit, which further increased industry savings and spurred a new wave of innovations (Falcone and Bjornstad, 2005). As one expert noted, PDC drill bits were an enabling technology for the horizontal drilling[3] that is so heavily relied upon for offshore drilling (Blankenship, 2009). An estimated 60% of worldwide oil and gas well footage was drilled using PDC drill bits in 2008 (Figure 5-2). A large share of this footage is attributable to horizontal drilling.

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[3] Horizontal drilling is the process of drilling and completing, for production, a well that begins as a vertical or inclined linear bore that extends from the surface to a subsurface location just above the target oil or gas reservoir, called the "kickoff point," then bears off on an arc to intersect the reservoir at the "entry point," and thereafter, continues at a near-horizontal attitude tangent to the arc to substantially or entirely remain within the reservoir until the desired bottom hole location is reached (U.S. DOE, 1993). The total linear footage used in the benefits calculations captures both vertical and linear drilling.

Table 5-6. A Matrix Assessing DOE Attribution of PDC Drill Bit Technology by Stage

Categories of Information Needed for Additionality Assessment	**Technology Timeline (Stage of Research, Development, and Commercialization)→**						
	Preliminary & Detailed Investigation	**Develop Components**	**Develop System**	**Validate/Demonstrate**	**Commercialize**	**Market Adoption**	**DOE Attribution**
What DOE support of SNL and others did	▪ Study applicability of PDC drill bits to geothermal fields	▪ Worked on improving performance of drill bits ▪ Financed contracts and R&D efforts with GE	▪ Conducted research on drill mechanics and hydraulics ▪ Developed STRATAPAX and PDCWEAR, which helped place cutters on the drill bit	▪ Sponsored wear and friction tests ▪ Helped establish best practices ▪ Held workshops, sponsored publications and presentations	▪ DOE efforts helped commercialize PDC bits	▪ DOE scientists and engineers contracted with consortium of drill bit manufacturers to continue improving the performance of PDC drill bits	**50%**
What others did (rival explanations)	▪ GE developed PDC in 1955 and first tested in the field 1973	▪ GE worked on DOE contracts	▪ GE used STRATAPAX to position cutters on drill bits ▪ Industry used PDCWEAR to create anti-whirl drill bits				
Driving/ restraining policies/ government forces (rival explanations)	▪ USGS study showed availability of geothermal fields around United States ▪ Oil crisis, U.S. government studied energy sources alternative to fossil fuels	▪ Oil crisis, U.S. government studied alternative energy sources to fossil fuels (including geothermal)			▪ Demand for oil went up, creating a demand for offshore drilling	▪ PDC bits became enabling technology for horizontal drilling widely used in offshore drilling ▪ Federal and State Tax Credits	

(continued)

Table 5-6. A Matrix Assessing DOE Attribution of PDC Drill Bit Technology by Stage, (continued)

Categories of Information Needed for Additionality Assessment	Technology Timeline (Stage of Research, Development, and Commercialization)→						
	Preliminary & Detailed Investigation	**Develop Components**	**Develop System**	**Validate/Demonstrate**	**Commercialize**	**Market Adoption**	**DOE Attribution**
Description of DOE influence	▪ **Very Important (50%)** ▪ DOE efforts helped consider applications of costly PDC drill bit technology	▪ **Very Important (50%)** ▪ DOE supported the technology at the time when it seemed too costly and unreliable	▪ **Dominant (70%)** ▪ Developed analytical tools that helped advance the application of the technology ▪ Greatly improves bonding of cutters to drill bit	▪ **Dominant (70%)** ▪ DOE efforts helped show that it is possible to overcome the short-comings of PDC drill bit technology with engineering and research	▪ **Influential (25%)** ▪ DOE's efforts helped deliver PDC bits right before there was an increase in demand for a similar technology, which helped the adoption of PDC bits	▪ **Influential (25%)** ▪ DOE's expertise remained available for the industry to use in their own R&D efforts	**50%**
Basis of evidence for influence	▪ Interviews with experts ▪ Articles ▪ Studies	▪ Interviews with experts ▪ Articles ▪ Studies	▪ Interviews with experts ▪ Articles ▪ Studies	▪ Interviews with experts ▪ Articles ▪ Studies	▪ Interviews with experts ▪ Articles ▪ Studies	▪ Interviews with experts ▪ Articles ▪ Studies	
The DOE effect	▪ Accelerated technology entry	▪ Improved performance	▪ Improved performance ▪ Changed costs	▪ Improved performance		▪ Improved performance	

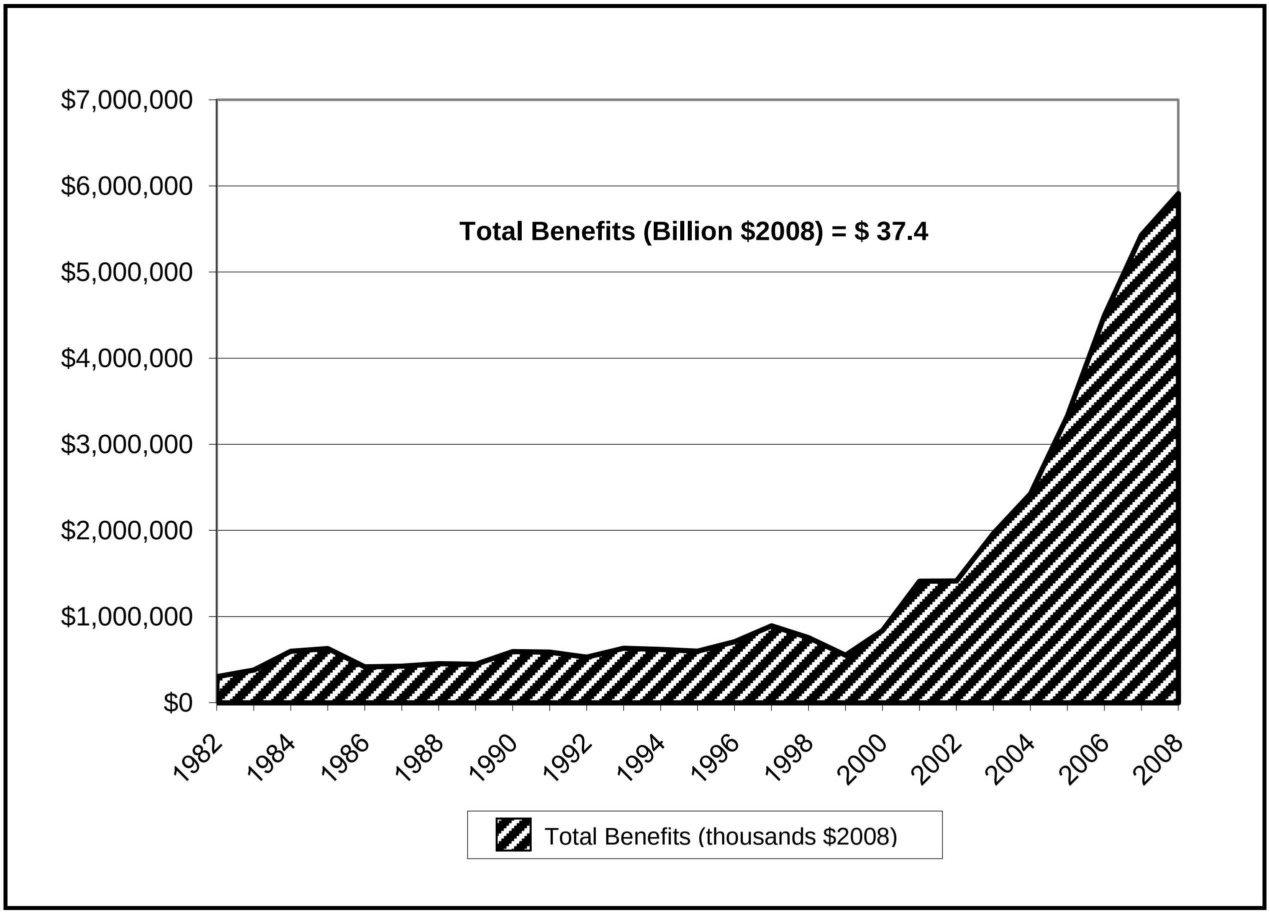
Sandia National Laboratories also helped with initial PDC bit development and commercial introduction. GE acknowledges that SNL helped deliver PDC drill bits to market several years before GE could on its own. As such, PDC drill bits were introduced on the eve of the drilling boom of the early 1980s, and the increased demand for drill bits during this period overcompensated for PDC bits' initial negative reputation. Had the PDC bits been introduced just a few years later, they would have failed to achieve significant market penetration because of the widespread entrenchment of roller bit technology (Papadakis and Link, 1997; Falcone and Bjornstad, 2005).

The published literature documents that, overall, SNL played a crucial role in innovation and market success of PDC drill bits. The PDCWEAR program code was used by almost half of the industry companies and represents a discrete piece of technology transferred from SNL to industry. Nevertheless, equally important was the incalculable amount of knowledge transferred since the beginning of SNL-industry collaboration in the 1970s, which included research on mechanics, physics, and hydraulics of PDC bit operation. As a result, based on the observable technology transfer, findings from published papers, and interviews, this study attributes 50% of the economic benefits from PDC bits to DOE. As shown in Table 5-6, DOE's influence varied across the stages of technology research development and commercialization, with DOE's greatest impact occurring during system development and validation/demonstration.

This attribution estimate is consistent with previous analysis. Papadakis and Link (1997) mention that about half of industry references to major improvements during a critical stage of the PDC drill bit product cycle were to Sandia's research. Papadakis and Link (1997) assigned 50% of economic benefits of PDC drill bit technology to SNL. Falcone and Bjornstad (2005) state that even though SNL's research was a critical precondition to market success, SNL partnered with industry stakeholders to bring innovation to the market. These partnerships were often equal; thus, Falcone and Bjornstad (2005) also assigned 50% of economic profits to SNL.

The total benefits of PDC drill bit technology were calculated in the previous section, and, as fifty percent of those savings are attributable to SNL, the total benefit from SNL's contributions to developing drill bit technology equaled $37.4 billion. The timeline of benefits is presented in Figure 5-3.

Figure 5-3. PDC Drill Bit Technology Benefits Attributable to DOE, 1982–2008



5.6 Benefit-Cost Analysis

DOE program expenditures and benefits associated with PDC drill bit research are presented in Table 5-7. These expenditures are based on a time series of appropriation items provided by DOE for EERE budgets from 1976 to 2008. The expenditures in Table 5-7 derive from appropriation line items associated with PDC drill bit research and demonstration activities, and represent approximately 1.6% of EERE's total GTP budget during this time period (see Appendix D for additional detail on GTP cost estimates). The PV of total expenditures (adjusted to $2008) equaled $26.5 million discounted at 7% from 1976 to 2008 ($41 million discounted at 3%). DOE's investment in PDC drill bit technology yielded net benefits with PV of $7.8 billion in net benefits ($18.5 billion discounted at 3%).

Table 5-7. PDC Drill Bit Technology Net Benefits Attributable to DOE, 1976–2008 (thousands $2008)

Year	Total Benefits	Program Expenses	Net Benefits
1976	$0	$2,081	-$2,081
1977	$0	$2,081	-$2,081
1978	$0	$2,081	-$2,081
1979	$0	$2,081	-$2,081
1980	$0	$2,081	-$2,081
1981	$0	$2,081	-$2,081
1982	$319,823	$2,081	$317,742
1983	$400,600	$2,081	$398,519
1984	$630,196	$2,081	$628,115
1985	$662,306	$2,081	$660,225
1986	$436,938	$2,081	$434,857
1987	$443,817	$1,844	$441,973
1988	$474,236	$1,683	$472,553
1989	$465,778	$1,601	$464,177
1990	$619,142	$1,490	$617,652
1991	$610,952	$1,586	$609,366
1992	$548,896	$1,575	$547,321
1993	$655,894	$1,455	$654,439
1994	$640,427	$1,335	$639,092
1995	$618,012	$1,341	$616,671
1996	$731,344	$1,474	$729,870
1997	$922,792	$1,558	$921,234
1998	$778,133	$1,817	$776,316
1999	$564,958	$1,979	$562,979
2000	$862,685	$2,045	$860,640
2001	$1,454,710	$2,188	$1,452,522
2002	$1,454,567	$2,188	$1,452,379
2003	$2,025,308	$2,188	$2,023,120
2004	$2,497,349	$2,188	$2,495,161
2005	$3,429,701	$2,188	$3,427,513
2006	$4,631,182	$2,188	$4,628,994
2007	$5,589,616	$2,188	$5,587,428
2008	$6,081,340	$2,188	$6,079,152
Undiscounted Totals	$38,550,702	$63,178	$38,487,524
PV[a] at 7%	**$7,813,212**	**$26,461**	**$7,786,751**
PV[a] at 3%	**$18,514,201**	**$41,015**	**$18,473,186**

[a] Base year is 1976, which is the first year of DOE program expenses.

Table 5-8 summarizes the results of benefit-cost analysis. In addition to net benefits with PV of $7.8 billion discounted at 7%, the ratio of benefits relative to DOE's expenditures was calculated (referred to as the BCR). The BCR discounted at 7% is calculated to be 295.3 (451.4 discounted at 3%), signifying large social benefits relative to program expenditures. The BCR deceases at higher discount rates, reflecting the timing of expenditures and benefits. IRR serves as a measure of an investment's return by comparing initial investments with discounted cash flows. The IRR for PDC drill bit technology project was 139%.

Table 5-8. PDC Drill Bit Technology Benefit-Cost Analysis Results

	Net Benefits (thousands $2008)	**Benefit-Cost Ratio**	**Internal Rate of Return**
PV[a] at 7%	$7,786,751	295.3	139%
PV[a] at 3%	$18,473,186	451.4	

[a] Base year is 1976, which is the first year of DOE program expenses.

6. GEOTHERMAL BINARY CYCLE POWER PLANTS: TECHNOLOGY IMPACT ASSESSMENT

6.1 Introduction

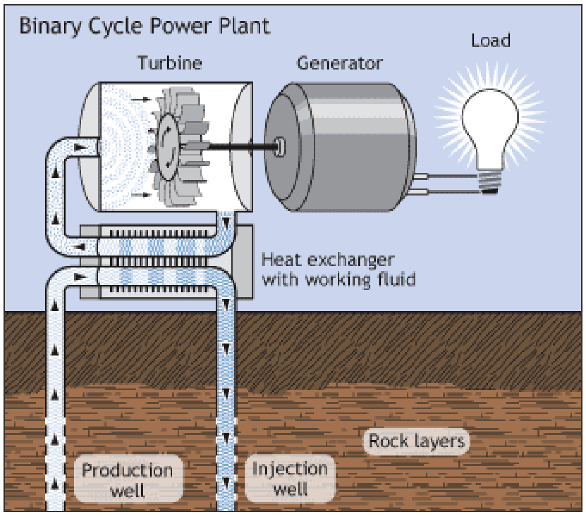
Binary cycle plants represented 16% of total installed geothermal capacity in the United States in 2008. Binary cycle geothermal power-plant technology enables efficient use of lower temperature resources through the use of a closed loop heat transfer system with a working fluid that has a low temperature boiling point. DOE assisted with the advancement of binary cycle plant technology in the United States by sponsoring research to lower costs and developing demonstration projects to showcase the technology's viability. This chapter discusses the technology history and social benefits of geothermal binary cycle plant technology attributable to DOE and DOE's role in accelerating its adoption. The PV of total benefits related to binary cycle technology is estimated to be approximately $237 million discounted at 7%. Approximately $42.8 million of these benefits (PV discounted at 7%) can be attributed to DOE through its research activities resulting from an investment with PV of $26.8 million discounted at 7%.

6.2 History of the Technology

Binary cycle geothermal power plants contain a system in which the heat from geothermal fluid is transferred to a secondary working fluid. With the heat transfer, the working fluid (which has a low temperature boiling point) is vaporized. Pressurized vapor then rotates a turbine connected to an electric generator. After it rotates the turbine, the cooled and condensed working fluid is pumped back into geothermal heat exchangers, completing the closed loop (see Figure 6-1). The main advantage of the binary cycle technology is that it is applicable to lower temperature resources, and therefore can be used in areas where other geothermal plant types cannot be built or are less optimal. Another benefit is that geothermal fluid (which often has solids dissolved in it) is never exposed to the ambient environment, reducing environmental pollution and providing higher power production potential from a given geothermal fluid flow (EERE/GTP, 2008a).

An assessment of geothermal resources carried out by the USGS in the 1970s found an abundance of lower temperature geothermal resources across the United States (EERE/GTP, 2008a). The power production of a geothermal plant varies with temperature, and without binary cycle technology, many of these lower temperature resources cannot be used economically (EERE/GTP, 2008a). For example, if the temperature of the resource is between 150°C and 190°C, flash-steam plants become less efficient, and hence, less economically attractive. The lower the temperature, the less economically feasible flash technology becomes. At temperatures below 150°C, even though wells could potentially flow spontaneously, the rates of flow would not be sufficient for economic viability. In addition, the chances of calcium carbonate buildup increase as compared to higher temperatures. One way to prevent the formation of buildup and to provide the production rates needed is to produce geofluid using down-well pumps. Once geofluid is produced in this manner, it is then not thermodynamically efficient to flash the fluid using a flash-steam plant, and it makes economic sense to use binary cycle technology instead (DiPippo, 2008).

Figure 6-1. Geothermal Binary Cycle Power Plant



Source: EERE/GTP (2008a).

The first prototype resembling today's binary cycle technology was adopted for a 250 kW power plant in Italy in 1912. The steam from wells was too contaminated to be sent directly to turbines, so a heat exchanger was used. In that heat exchanger, geothermal steam boiled water that then drove the turbine (DiPippo, 2008). In later years, the enabling technology for geothermal binary plants, the Organic Rankine Cycle, was commercialized by the Ormat corporation in 1965 (Leslie et al., 2009). The first geothermal binary plant to use the Organic Rankine Cycle technology was put into operation in Russia in 1967. It was rated at 670 kW and ran successfully for several decades (DiPippo, 2008).

Even though binary cycle technology was available in the 1960s and 1970s, it was widely viewed at that time as unproven and uneconomical, and attracted little commercial interest in the United States. As a result, in the mid-1970s, DOE began working to increase the efficiency and lower the operating costs of binary power plants. Most of DOE's small and larger scale demonstration plants (Raft River, Heber, and Pleasant Bayou) included some innovative aspects. After building larger scale demonstration plants, DOE's focus shifted to improving the efficiency of the binary cycle. These efforts were considered critical to demonstrating the viability and lowering the costs of binary cycle geothermal energy, making more resources economically viable (EERE/GTP, 2008b).

To support its research activities, DOE developed a set of facilities in Idaho at Raft River, in California at East Mesa (Heber and Salton Sea), and later in Texas at Pleasant Bayou. Some of these facilities were constructed utilizing technologies that had not been previously used, including multiple boiling binary cycles, supercritical binary cycles using working fluid mixtures, and hybrid cycles for geo-pressured geothermal resources. DOE sponsored research at its laboratories and at universities, and granted contracts to private industry to perform a research at these facilities (EERE/GTP, 2008a).

When the geothermal industry started to build binary cycle plants in the late 1980s, field validation of technologies shifted from DOE facilities to commercial geothermal plants. By the early 1990s, DOE had shut down the majority of its research facilities, but laboratory personnel continued to work closely with the industry on field validation of the economic feasibility of power production. The results of these efforts were technology improvements to the operation and maintenance of geothermal power plants (EERE/GTP, 2008a).

Bolstered by the introduction of various state and federal policies in response to the 1976 energy crisis, installation of binary cycle plants saw significant growth in the late 1980s and early 1990s. Table 6-1 lists all the binary cycle geothermal plants operating in the United States in the summer of 2008. Among these 26 plants are 72 units with a total installed capacity of 408 MW. Even though binary cycle plants account for 55% of units built in the United States, they account for only 16% of the installed geothermal MW capacity.

6.3 Next Best Alternative

Binary cycle power plants offer an improvement over existing geothermal plant technology. The next best alternative technology differs depending on the temperature of the reservoir where binary cycle is installed:

- In reservoir temperature ranges of 150°C to 190°C, flash cycle technology is economically viable, but has lower electricity generation productivity as compared to binary cycle due to lower conversion efficiency. Thus, in this temperature range, the next best alternative is a traditional flash cycle geothermal plant.
- In the temperature range below 150°C, flash cycle technology is not economically viable and no other geothermal technology is available. In this temperature range, the next best alternative is a generation from a mix of fossil fuels.

Given that more than 80% of U.S. geothermal resources fall below 150°C, binary cycle technology has increased the cost-effectiveness of constructing geothermal plants at sites otherwise unsuitable for geothermal electricity generation. As previously stated, in this temperature range, the next best alternative would be a coal factory.

Table 6-1. Geothermal Binary Cycle Power Plants in the United States, 2008

Binary Power Plant	State	Start Year	Number of Units	Installed Capacity (MW)	Average Reservoir Temperature (°C)
Mammoth Pacific I	CA	1984	4	10.0	183
Wabuska	NV	1984	3	2.2	118
Ormesa I	CA	1986	1	44.0	154
Steamboat I	NV	1986	7	8.4	188
Ormesa II	CA	1987	1	18.0	154
San Emidio (Empire)	NV	1987	4	4.8	152
Soda Lake I	NV	1987	4	5.1	182
Amedee	CA	1988	2	1.6	116
Ormesa IE	CA	1988	1	10.0	154
Steamboat IA	NV	1988	2	3.0	188
Ormesa IH	CA	1989	1	13.2	154
Stillwater	NV	1989	1	16.0	154
Mammoth Pacific II	CA	1990	NA	15.0	183
Soda Lake II	NV	1990	6	18.0	182
Cove Fort 2	UT	1990	3	2.3	NA
Brady Hot Springs	NV	1992	3	27.0	182
Steamboat II	NV	1992	2	29.0	188
Steamboat III	NV	1992	2	24.0	188
Heber II	CA	1993	7	48.0	171
Puna Geo Venture	HI	1993	10	20.0	149
Richard Burdett	NV	2005	2	30.0	188
Chena Hot Springs	AK	2006	2	0.5	74
Galena 2	NV	2007	1	15.0	188
Heber South	CA	2008	1	10.0	171
Raft River	ID	2008	1	13.0	149
Galena 3	NV	2008	1	20.0	188
Total Binary			**72**	**408.1**	
Total Geothermal			**130**	**2,600.0**	
Binary Share of All Geothermal			**55%**	**16%**	

Source: GEA (2009a).

6.4 Benefits Calculations

This section estimates the benefits associated with using binary cycle geothermal power plant technology.[1] The benefits of binary cycle plant technology include the economic benefits of increased conversion efficiency of binary cycle technology over flash technology and the environmental benefits of switching away from fossil fuels. Benefits are calculated separately for the two temperature ranges of

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[1] Not all the benefit associated with binary cycle plants can be attributed to DOE. Some development and implementation of the binary cycle technology came from commercial sector (e.g., Ormat commercialized binary cycle technology using solar ponds as the heat source). Thus, as discussed in Section 6.5, benefits attributed to DOE are based on the acceleration of the benefits quantified in this section.

geothermal resources described above. Table 6-2 summarizes the key parameters and assumptions used to estimate benefits.

Table 6-2. Key Parameters and Assumptions Used in the Binary Cycle Power Plants Benefits Analysis

Parameters/Assumptions	Source
Binary plants are 15% more efficient than flash plants in the mid-level temperature range	Average of three efficiency studies (Brugman et al., 1994).
Geothermal energy offsets fossil fuel-fired generation	60% Coal, 39% natural gas, and 1% petroleum[2] (see Appendix C for calculations and sources)
DOE activities accelerated the development and deployment of geothermal electricity generation by 2 years	Published literature, interviews with industry and DOE experts

6.4.1 Economic Benefits

Economic Benefits for 150°C to 190°C Binary Plants

In the 150°C to 190°C range (referred to as “mid-level temperature range” in the remainder of the report), the best alternative technology would be geothermal flash power plant technology. These temperature boundaries are determined by technological limitations of flash and binary cycle technologies (Bronicki, 2002). Most the benefits of binary plants are associated with the incremental productivity gains resulting from the conversion efficiency gains of the binary cycle technology. This is captured by the market value of the additional electricity produced.[3]

Binary cycle plant technology allowed more efficient power plants using mid-level temperature resources (150°C to 190°C) to be built. The Electric Power Resource Institute (EPRI) sponsored a study in the mid-1990s that evaluated the performance of binary and flash plants for different geothermal fields. The findings of these studies were published in EPRI’s *Next Generation Geothermal Power Plants* (Brugman et al., 1994). Three fields had both binary and flash plants in the mid-level temperature range: Raft River, Vale, and Surprise Valley (Brugman et al., 1994). Table 6-3 presents the brine rate (in thousands of pounds per hour) of the facilities in these fields. As the table shows, binary plants have higher conversion efficiency than flash plants (e.g., less brine is required to generate an equal amount of energy). It is also worth noting that conversion efficiency decreases as the temperature of the source increases. Based on these observations, binary plants are 15% more efficient than flash plants in the mid-level temperature range.

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[2] This is an average value of fuel mix across the states.

[3] Through interviews with industry experts, it was determined that the capital and operating costs of binary cycle plants and flash plants are comparable in the mid-level temperature range. Figures 5-2 and 5-4 in the Electric Power Research Institute’s (EPRI’s) Next Generation Geothermal Power Plants Report (Brugman et al., 1994) also support this claim. Thus, no cost differences are included in the analysis.

Table 6-3. Increase in Conversion Efficiency of Binary vs. Flash Power Plants in the Mid-Level Temperature Range

Reservoir	Brine Rate (1,000 lb/hr)		Percentage Increase in Conversion Efficiency
	Binary	Flash	
Raft River, ID at 150°C	12,384	15,392	19.5%
Vale, OR at 166°C	8,678	10,375	16.4%
Surprise Valley, CA at 190°C	6,800	7,473	9.0%
Average			**15.0%**

Source: Brugman et al. (1994).

This information allowed us to calculate total energy generated by binary plants in the mid-level temperature range. Fifteen percent of the electricity generated is attributable to higher conversion efficiency of binary plants over flash plants in the mid-level temperature range. That share was then multiplied by the historical price of electricity to calculate the economic benefits of binary technology. These calculations are presented in Table 6-4. Total conversion efficiency benefits equaled $109.9 million.

Economic Benefits for Less than 150°C Binary Plants

For geothermal resources less than 150°C (referred to as “low temperature range” in the remainder of the report), there was no best alternative technology available for producing geothermal power. Thus, in the absence of binary cycle technology, no geothermal plant would have been installed. As a result, the benefits are associated with the full output of the binary cycle geothermal plant. No economic benefits are calculated because the production costs for geothermal power plants are comparable to fossil fuel plants. Thus, the benefits are primarily environmental, producing renewable energy that offsets generation from a mix of fossil fuels (Glitnir, 2008). Environmental health benefits are quantified in Section 6.4.2.

Table 6-4. Conversion Efficiency Benefits of Binary Cycle Power Plants in the Mid-Level Temperature Range, 1984–2008

Year	*(a)* Geothermal Electricity Generated (MWh)[a]	*(b)* Share of Binary Plants Capacity Relative to All Geothermal Plants Capacity[b]	*(c)* Share of Binary Plants Capacity in Mid-Level Temperature Relative to All Binary Plants[b]	*(d = a * b * c)* Electricity Generated By Binary Plants in Mid-level Temperature Range (MWh)	*(e = d * 15% from Table 6-2)* Electricity Generated due to Conversion Efficiency of Binary (MWh)	*(f)* Electricity Price, Including Taxes (thousands $2008/MW)[c]	*(g = f * e / 1,000)* Conversion Efficiency Benefits (thousands $2008)
1984	7,740,504	1.0%	82.0%	63,472	9,521	$113.4	$1,080
1985	9,325,230	0.8%	82.0%	61,174	9,176	$113.5	$1,041
1986	10,307,954	3.9%	96.6%	388,342	58,251	$111.0	$6,466
1987	10,775,461	5.2%	97.6%	546,876	82,031	$106.7	$8,753
1988	10,300,079	5.3%	96.5%	526,798	79,020	$102.8	$8,123
1989	14,593,443	5.9%	97.2%	836,905	125,536	$100.7	$12,641
1990	15,434,271	7.0%	97.8%	1,056,630	158,495	$98.7	$15,643
1991	15,966,444	7.0%	97.8%	1,093,063	163,959	$97.9	$16,052
1992	16,137,962	10.1%	98.5%	1,605,485	240,823	$96.7	$23,288
1993	16,788,565	12.4%	92.6%	1,927,730	289,160	$96.1	$27,788
1994	15,535,453	12.4%	92.6%	1,783,843	267,576	$93.9	$25,125
1995	13,378,258	12.4%	92.6%	1,536,145	230,422	$91.7	$21,130
1996	14,328,684	12.2%	92.6%	1,618,740	242,811	$89.6	$21,756
1997	14,726,102	12.2%	92.6%	1,663,637	249,546	$87.9	$21,935
1998	14,773,918	12.2%	92.6%	1,669,039	250,356	$85.5	$21,405
1999	14,827,013	12.2%	92.6%	1,675,037	251,256	$83.0	$20,854
2000	14,093,158	12.0%	92.6%	1,566,032	234,905	$83.3	$19,568
2001	13,740,501	12.0%	92.6%	1,526,844	229,027	$87.2	$19,971

(continued)

[a] Source: U.S. DOE (2010d).

[b] Source: GEA (2009a).

[c] Source: U.S. DOE (2009).

[d] Base year is 1976, which is the first year of DOE program expenses.

Table 6-4. Conversion Efficiency Benefits of Binary Cycle Power Plants in Mid-Level Temperature Range, 1984–2008, (continued)

Year	***(a)*** **Geothermal Electricity Generated (MWh)**[a]	***(b)*** **Share of Binary Plants Capacity Relative to All Geothermal Plants Capacity**[b]	***(c)*** **Share of Binary Plants Capacity in Mid-Level Temperature Relative to All Binary Plants**[b]	***(d = a * b * c)*** **Electricity Generated By Binary Plants in Mid-level Temperature Range (MWh)**	***(e = d * 15% from Table 6-2)*** **Electricity Generated due to Conversion Efficiency of Binary (MWh)**	***(f)*** **Electricity Price, Including Taxes (thousands $2008/MW)**[c]	***(g = f * e / 1,000)*** **Conversion Efficiency Benefits (thousands $2008)**
2002	14,491,310	12.0%	92.6%	1,610,274	241,541	$84.8	$20,483
2003	14,424,231	12.0%	92.6%	1,602,821	240,423	$85.8	$20,628
2004	14,810,975	12.0%	92.6%	1,645,796	246,869	$85.3	$21,058
2005	14,691,745	13.0%	93.2%	1,780,052	267,008	$88.3	$23,577
2006	14,568,029	12.7%	93.1%	1,722,480	258,372	$93.5	$24,158
2007	14,637,213	13.2%	93.4%	1,804,593	270,689	$93.3	$25,255
2008	14,859,238	14.5%	90.9%	1,958,522	293,778	$98.2	$28,849
Total	345,255,741			33,270,329	4,990,549		
Undiscounted Total							$456,627
PV [d] at 7%							**$109,939**

[a] Source: U.S. DOE (2010d).

[b] Source: GEA (2009a).

[c] Source: U.S. DOE (2009).

[d] Base year is 1976, which is the first year of DOE program expenses.

6.4.2 Environmental Benefits

The environmental benefits of geothermal binary plants make them valuable assets in reducing air pollutants such as particulate matter (PM), sulfur oxides (SO_x) and nitrous oxides (NO_x), and in reducing greenhouse gases such as carbon dioxide (CO_2). Binary plants do not emit gases, as opposed to competing generation technologies such as coal-fired fossil fuel plants, which generate vast amounts of air pollutants.

Environmental benefits are associated with both include:

- The environmental health benefit of this additional electricity offsetting generation from a mix of fossil fuels (Glitnir, 2008), and
- The incremental environmental health benefits associated with what would have been flash cycle–generated electricity but is now binary cycle–generated electricity.[3]

The Co-Benefits Risk Assessment (COBRA) model was used to calculate the environmental health benefits of the reduction in air pollution resulting from the use of binary cycle power plants. A discussion of this model is contained in Appendix C. The input to the model is the reduction (tons/year) of PM, NO_x, and SO_2 from geothermal energy generated by binary cycle compared to the next best alternative. As discussed above, the next best alternative is generation from a mix of fossil fuels for low temperature range binary cycle and flash cycle geothermal for mid-level temperature binary cycle. Where flash technology is the alternative, the electricity generated due to increased productivity (approximately 15%, as was shown in Section 6.4.1) will offset fossil fuel generation. The remaining 85% will offset flash cycle geothermal generation. Table 6-5 shows that offsetting fossil fuel generation accounts for the majority of the emission reductions that are input into the COBRA model.[4]

Table 6-5. Emission Reductions Associated with Binary Cycle Power Plants, 2008

				Total Emission Reduction		
Temperature Range	**Scenario**	**Alternative Technology**	**GWh (2008)**	**PM Tons (2008)**	**SO_2 Tons (2008)**	**NO_x Tons (2008)**
Mid–level: 150°–190°C	Binary cycle	Flash	1,665[a]	321	0	0
	15% increased productivity	Fossil fuel mix[d]	294[b]	757	382	200
Low: <150°C	Binary cycle	Fossil fuel mix[d]	196[c]	451	255	134
Total (2008)			**2,155**	**1,530**	**637**	**334**

[a] Year 2008 value from Table 6-4 Column (d) x 85% (percentage offsetting flash cycle geothermal generation)
[b] Year 2008 value from Table 6-4 Column (d) x 15% (efficiency gain offsetting fossil fuel generation)
[c] Year 2008 value from Table 6-4 Column (a) x Table 6-4 Column (b) x (1 - Table 6-4 Column (c))
[d] See Appendix C for calculations.

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[3] Flash cycle has relatively low emissions (especially relative to fossil fuel plants). However, binary cycle has no emissions, because it is a closed loop system. Hence, this incremental reduction in emissions is included in the benefit analysis.

[4] It should be noted that flash cycle geothermal is a significant source of CO_2 emissions, which historically have not been classified as a pollutant, and hence are not included in the benefits analysis. However, in the future, reductions in CO_2 are likely to have a monetary value as greenhouse gas emissions become increasingly important and potential CO_2 mitigation policies are enacted.

Table 6-6 shows the time series of emission reductions attributable to DOE, including GHG reductions.

Table 6-6. Binary Cycle Power Plants Emission Reductions

Year	Fossil Fuel Power Offset by Binary Cycle Power Production (MWh)[b]	Particulates (short tons)	SO_2 (short tons)	NO_x (short tons)	CO_2 Equivalent Reduction[c] (thousand metric tons)
1984	17,598	55	23	12	16
1985	16,961	53	22	12	15
1986	91,397	285	119	62	82
1987	127,390	398	166	87	115
1988	124,111	388	161	85	112
1989	195,751	611	255	133	176
1990	245,629	767	319	167	221
1991	254,098	794	330	173	229
1992	370,566	1,157	482	253	334
1993	473,293	1,478	615	323	426
1994	437,966	1,368	570	298	395
1995	377,152	1,178	490	257	340
1996	397,430	1,241	517	271	358
1997	408,453	1,276	531	278	368
1998	409,780	1,280	533	279	369
1999	411,252	1,284	535	280	370
2000	384,490	1,201	500	262	346
2001	374,868	1,171	487	255	338
2002	395,352	1,235	514	269	356
2003	393,522	1,229	512	268	355
2004	404,073	1,262	525	275	364
2005	434,222	1,356	565	296	391
2006	420,629	1,314	547	287	379
2007	439,266	1,372	571	299	396
2008	489,846 [a]	1,530	637	334	441
Total	**8,095,095**	**25,280**	**10,527**	**5,517**	**7,293**

[a] Total Binary Electricity Generated offsetting fossil fuel from table [Table 6-5]

[b] Years 1984-2007 scaled back from 2008 data using Total Binary Power Production Table 6-4 column (a) X column (b)

[c] Calculation based on Electricity Produced by Binary Plants (a) and Carbon Dioxide Emission Rates: Coal 2.117; Natural Gas 1.314; Oil 1.915 pounds per KWh (U.S. DOE, 2010c).

The annual health benefits associated with emission reductions from using binary cycle geothermal are estimated to be $37.1 million in 2008, and are presented in Table 6-7. At $34.1 million per year, avoided mortality accounts for the majority of benefits.[5] For a detailed discussion of the environmental benefits calculation, refer to Appendix C.

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[5] The mean value for avoiding one statistical death in the COBRA model is $5.5 million ($2000) (USEPA, 2006).

Table 6-7. Environmental Health Benefit Associated with Binary Cycle Power Plants, 2008

Health Risks	Incidence (number)	Cost (thousands $2008)
Mortality	5	$34,113
Infant mortality	0	$104
Chronic bronchitis	4	$1,620
Nonfatal heart attacks	8	$860
Respiratory hospital admissions	1	$13
Cardiovascular-related hospital admissions	2	$60
Acute bronchitis	9	$3
Upper respiratory symptoms	81	$2
Lower respiratory symptoms	107	$2
Asthma emergency room visits	3	$1
Minor restricted activity days	4,500	$280
Lost work days	763	$61
Total	**5,483**	**$37,119**

The estimated benefits for 2008 have been scaled (accounting for the time series of binary cycle power plant total power production, as well as population growth) to estimate benefits for previous years. The time series of environmental health benefits is presented in Table 6-8.

Table 6-8. Time Series of Environmental Health Benefits of Binary Cycle Power Plants in the United States, 1984–2008

Year	*(a)* Fossil Fuel Power Offset from Binary Cycle Power Production (MWh)[a]	*(b)* U.S. Population[b]	Environmental Health Benefits[c] (thousands $2008)
1984	17,598	235,824,902	$1,034
1985	16,961	237,923,795	$1,006
1986	91,397	240,132,887	$5,470
1987	127,390	242,288,918	$7,692
1988	124,111	244,498,982	$7,563
1989	195,751	246,819,230	$12,041
1990	245,629	249,464,396	$15,271
1991	254,098	252,153,092	$15,968
1992	370,566	255,029,699	$23,552
1993	473,293	257,782,608	$30,406
1994	437,966	260,327,021	$28,414
1995	377,152	262,803,276	$24,702

(continued)

[a] Total Binary Electricity Generated [Table 6-5] – Binary Electricity Replacing Flash Technology [Table 6-5], scaled by Column (a) x Column (b) [Table 6-4]

[b] Source: U.S. Bureau of the Census (2000, 2009).

[c] Health Benefits in 2008 [$37.1 Million from Table 6-7] scaled by Column (a) and Column (b).

[d] Base year is 1976, which is the first year of DOE program expenses.

Table 6-8. Time Series of Environmental Health Benefits of Binary Cycle Power Plants in the United States, 1984–2008 (continued)

Year	*(a)* Fossil Fuel Power Offset from Binary Cycle Power Production (MWh)[a]	*(b)* U.S. Population[b]	Environmental Health Benefits[c] (thousands $2008)
1996	397,430	265,228,572	$26,270
1997	408,453	267,783,607	$27,259
1998	409,780	270,248,003	$27,599
1999	411,252	272,690,813	$27,948
2000	384,490	282,171,936	$27,038
2001	374,868	285,039,803	$26,629
2002	395,352	287,726,647	$28,349
2003	393,522	290,210,914	$28,462
2004	404,073	292,892,127	$29,495
2005	434,222	295,560,549	$31,984
2006	420,629	298,362,973	$31,277
2007	439,266	301,290,332	$32,983
2008	489,846	304,059,724	$37,119
Undiscounted Total			$555,530
PV[d] at 7%			**$127,034**

[a] Total Binary Electricity Generated [Table 6-5] – Binary Electricity Replacing Flash Technology [Table 6-5], scaled by Column (a) x Column (b) [Table 6-4]

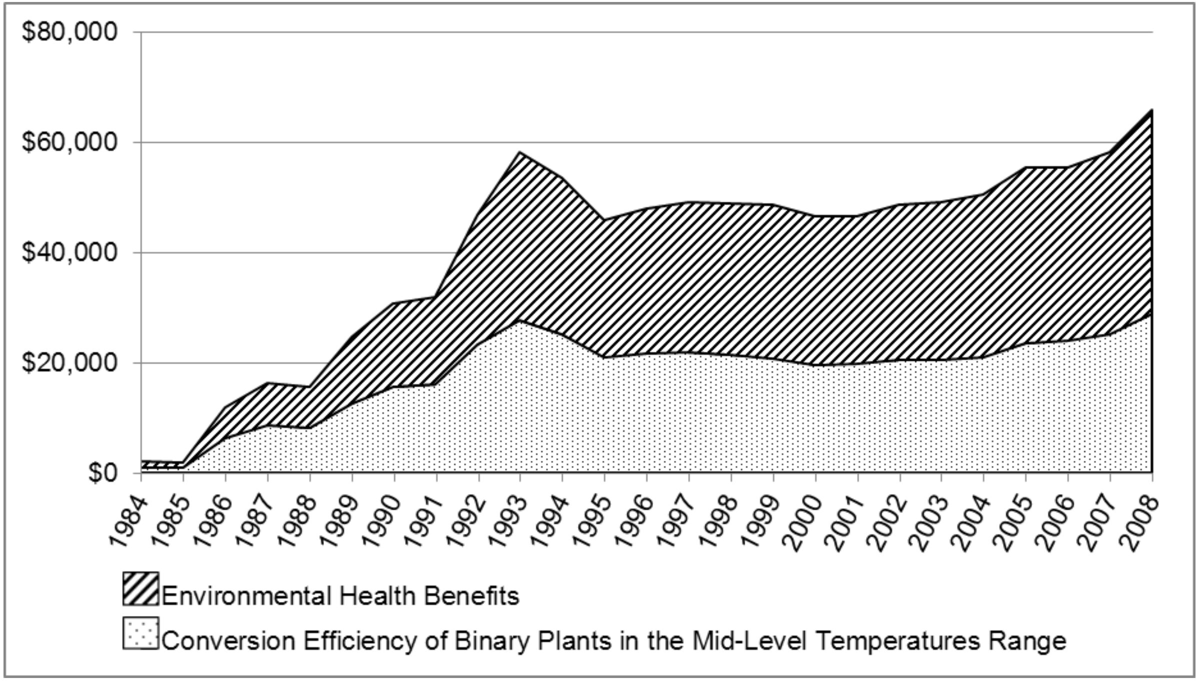
[b] Source: U.S. Bureau of the Census (2000, 2009).

[c] Health Benefits in 2008 [$37.1 Million from Table 6-7] scaled by Column (a) and Column (b).

[d] Base year is 1976, which is the first year of DOE program expenses.

Figure 6-2 shows the total benefits of geothermal binary cycle plant technology, which include environmental health benefits and conversion efficiency benefits.

Figure 6-2. Total Benefits of Binary Cycle Power Plants (thousands $2008)



Total undiscounted benefits equaled approximately $556 million from 1984 to 2008 (PV of $237 million discounted at 7%).

6.4.3 Security Benefits

Security benefits derive from reducing the probability and potential impact of oil and natural gas disruptions and price shocks or other energy system disruptions that would damage or disrupt the economy, environment, or national security of the United States. The benefits are realized through substitution of a volume of oil and natural gas, which otherwise would be combusted to produce electricity, with geothermal electricity generation technology. Table 6-9 presents the reduction in 4.9 billion cubic feet of natural gas or 862 thousand barrels of oil equivalent.

Table 6-9. Security Benefits of Binary Cycle Power Plants Attributable to DOE, 1984–2008

Year	Fossil Fuel Power Offset from Binary Cycle Power Production (MWh)[a]	Million Cubic Feet of Natural Gas[b]	BOE (Thousand Barrels of Oil Equivalent)[b]
1984	17,598	10.6	1.9
1985	16,961	10.2	1.8
1986	91,397	54.9	9.7
1987	127,390	76.5	13.6
1988	124,111	74.6	13.2
1989	195,751	117.6	20.8
1990	245,629	147.6	26.2
1991	254,098	152.6	27.1
1992	370,566	222.6	39.5
1993	473,293	284.3	50.4
1994	437,966	263.1	46.6
1995	377,152	226.6	40.2
1996	397,430	238.8	42.3
1997	408,453	245.4	43.5
1998	409,780	246.2	43.6
1999	411,252	247.1	43.8
2000	384,490	231.0	40.9
2001	374,868	225.2	39.9
2002	395,352	237.5	42.1
2003	393,522	236.4	41.9
2004	404,073	242.7	43.0
2005	434,222	260.9	46.2
2006	420,629	252.7	44.8
2007	439,266	263.9	46.8
2008	489,846	294.3	52.2
Total	**8,095,095**	**4,863**	**861.8**

[a] Total Binary Electricity Generated [Table 6-5] – Binary Electricity Replacing Flash Technology [Table 6-5], scaled by Column (a) x Column (b) [Table 6-4]

[b] DOE Attribution was applied by multiplying million cubic feet of natural gas or BOE by the attribution factor, 18.1% [Table 6-11 discounted total-benefits attributable to DOE/ discounted total 2-year acceleration scenario]

6.5 Attribution Share

Since the 1970s, DOE's GTP has dedicated substantial funding to conduct research and development of energy conversion technologies compatible with liquid dominated geothermal resources. The summary of DOE attribution is shown in Table 6-10. The goal of DOE's energy conversion research was to lower the cost of producing electricity from lower temperature geothermal resources. DOE initially supported the construction and operation of a number of small (<100 kW) plants in the mid- to late-1970s. DOE developed test facilities in California at the Salton Sea, East Mesa, and Heber sites; in Idaho at the Raft River site, and in Texas at the Pleasant Bayou site (EERE/GTP, 2008a). The power plants constructed at these test sites used "first-use" technologies such as: multiple boiling binary cycles, supercritical binary cycles using working fluid mixtures, and hybrid cycles for geo-pressured geothermal resources.

As DOE stopped building demonstration plants (in the mid-1980s), efforts shifted to improving efficiency of binary cycle. These improvements were then validated at both DOE's field locations and commercial plants. In parallel with the energy conversion research taking place at national laboratories, DOE also contracted with geothermal industry to conduct research at their facilities.

Following construction of test plants by DOE, there was little commercial development of binary plants by the industry. Construction took off the mid-1980s, when the first plant at Mammoth was built. After that, a number of binary plants were constructed until the mid-1990s, when activity slowed. Some of the entities involved in building the commercial plants were also involved in the earlier DOE research, and this experience provided some level of confidence in the binary technology. Early DOE work with binary prototype systems also demonstrated the viability of the technology to project developers and financiers.

The main impact of DOE on binary cycle technology has been the demonstration of commercial applicability of binary cycle technology, and provision of guaranteed loans, which helped industry to obtain financing. Both of these factors accelerated the technology's entry into the market. All interview participants mentioned that DOE had some effect on accelerating the market penetration of binary cycle technology. When asked to quantify DOE's impact, estimates of the acceleration effect ranged from less than five years to more than six months. Based on these estimates, an acceleration effect of two years is used to capture DOE's attribution.

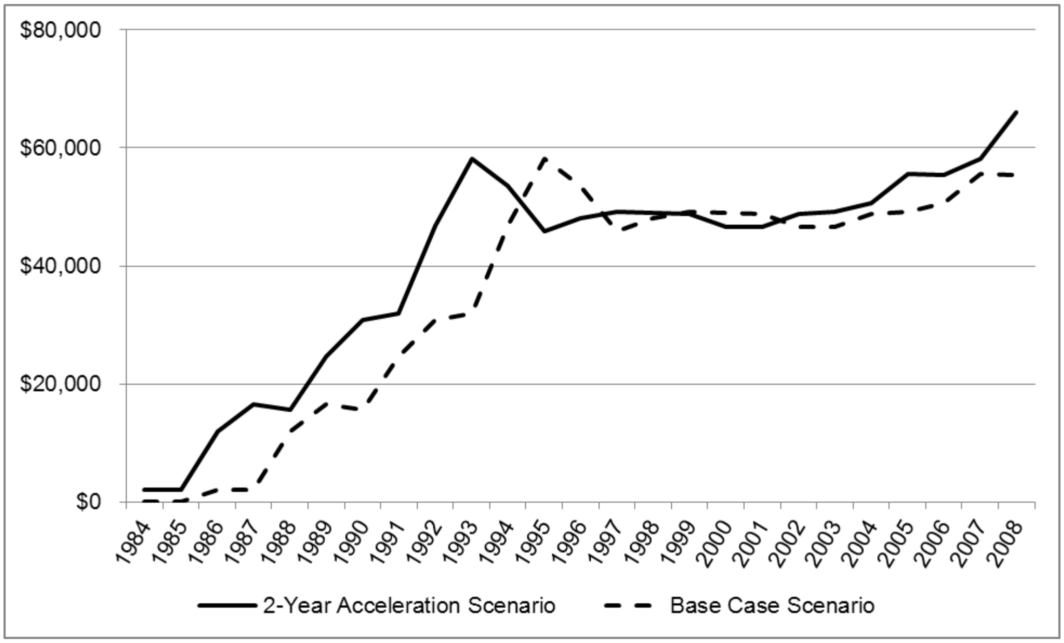
Table 6-10. A Matrix for Assessing DOE Attribution of Binary Cycle Power Plants by Stage

Categories of Information Needed for Additionality Assessment	Technology Timeline (Stage of Research, Development, and Commercialization)→						
	Preliminary & Detailed Investigation	**Develop Components**	**Develop System**	**Validate/Demonstrate**	**Commercialize**	**Market Adoption**	**DOE Attribution**
What DOE did	▪ Began work on efficiency of power plants and equipment operation.	▪ First application of multiple boiling binary cycles and other technologies (including mixed working fluids, super-critical cycles, and metastable turbine expansions)		▪ Raft River DOE demonstration 60 kW, 5 MW plants ▪ Heber CA, East Mesa, CA, and Pleasant Bayou, TX plants ▪ Mammoth Pacific MPI, Mammoth Lakes CA		▪ DOE experts continued to work under contracts with the industry	2-year Acceleration Effect
What others did (Rival Explanations)	▪ Binary cycle plant built in Kamchatka, USSR, in 1967	▪ Prototype for binary cycle developed in Israel by Ormat	▪ Organic Rankine Cycle commercialized by Ormat		▪ DOE used loan guarantee program to sponsor binary plant construction by Ben Holt, Ormat, and others ▪ Granted contracts to perform research at test plants built by DOE		
Driving/restraining policies/government forces (Rival Explanations)	▪ Identified abundance of low temperature resources around United States (USGS)					▪ Standard offer 4 tax credits ▪ Renewable Portfolio Standards	
Description of DOE influence		▪ Tested new components and solutions on test plants built by DOE		▪ Demonstrated commercial applicability of binary cycle plants	▪ Sponsored research at laboratories and universities		
Basis of evidence for influence	▪ Articles	▪ Interviews with partners ▪ Articles	▪ Articles	▪ Interviews with partners and stakeholders ▪ Articles	▪ Interviews with stakeholders		
The DOE effect		▪ Improved performance		▪ Accelerated technology entry	▪ Accelerated technology entry		

Source: DiPippo (2008).

Figure 6-3 demonstrates the acceleration scenario. The benefits attributable to DOE are composed of the difference between benefits acquired under acceleration and base case benefits.

Figure 6-3. Benefits of Binary Cycle Power Plants Attributable to DOE



These benefits are represented by the area below the solid line and above the dotted line on the graph. Calculation of these benefits is also presented in Table 6-11. The PV of total benefits attributable to DOE equaled approximately $42.8 million (discounted at 7%) from 1984 to 2008.

Table 6-11. Economic Benefits of Binary Cycle Power Plants Attributable to DOE by Year, 1984–2008 (thousands $2008)

Year	*(a)* 2-Year Acceleration Scenario[a]	*(b)* Base Case Scenario	*(a − b)* Benefits Attributable to DOE
1984	$2,114	–	$2,114
1985	$2,047	–	$2,047
1986	$11,936	$2,114	$9,822
1987	$16,445	$2,047	$14,398
1988	$15,686	$11,936	$3,750
1989	$24,682	$16,445	$8,238
1990	$30,914	$15,686	$15,229
1991	$32,019	$24,682	$7,337
1992	$46,840	$30,914	$15,926
1993	$58,194	$32,019	$26,175
1994	$53,540	$46,840	$6,700
1995	$45,831	$58,194	-$12,363
1996	$48,026	$53,540	-$5,514
1997	$49,194	$45,831	$3,362
1998	$49,004	$48,026	$978
1999	$48,803	$49,194	-$391

(continued)

[a] Economic Benefits = conversion efficiency benefits [Column (g), Table 6-4)] + health benefits [Column (c), Table 6-8)]

Table 6-11. Economic Benefits of Binary Cycle Power Plants Attributable to DOE by Year, 1984–2008 (thousands $2008), (continued)

Year	*(a)* 2-Year Acceleration Scenario[a]	*(b)* Base Case Scenario	*(a − b)* Benefits Attributable to DOE
2000	$46,606	$49,004	-$2,399
2001	$46,601	$48,803	-$2,202
2002	$48,832	$46,606	$2,226
2003	$49,090	$46,601	$2,489
2004	$50,553	$48,832	$1,721
2005	$55,561	$49,090	$6,471
2006	$55,435	$50,553	$4,882
2007	$58,238	$55,561	$2,677
2008	$65,968	$55,435	$10,533
Undiscounted Total	$1,012,158	$887,952	$124,206
PV[a] at 7%	**$236,973**	**$222,254**	**$42,848**

[a] Benefits = conversion efficiency benefits [Column (g), Table 6-4)] + health benefits [Column (c), Table 6-8)]

[b] Base year is 1976, which is the first year of DOE program expenses

6.6 Benefit-Cost Analysis

DOE program expenditures associated with binary cycle research are presented in Table 6-12. These expenditures are based on a time series of appropriation items provided by DOE for EERE budgets from 1976 to 2008. The expenditures in Table 6-12 are built up from appropriation line items associated with binary cycle research and demonstration activities, and represent approximately 1.6% of EERE’s total GTP budget during this time period. The PV of total expenditures (adjusted to $2008) equaled $26.8 million discounted at 7% from 1976 to 2008 ($40.7 million discounted at 3%). Binary cycle expenditures peaked between 1978 and 1982. DOE’s investment in binary cycle power plant technology yielded net benefits with PV of $16.0 million discounted at 7% ($35.6 million discounted at 3%).

Table 6-12. Net Benefits of Binary Cycle Power Plants Attributable to DOE, 1976–2008 (thousands $2008)

Year	Total Benefits[a]	Program Expenditures	Net Benefits
1976	$0	$2,036	-$2,036
1977	$0	$2,036	-$2,036
1978	$0	$2,036	-$2,036
1979	$0	$2,036	-$2,036
1980	$0	$2,036	-$2,036
1981	$0	$2,036	-$2,036
1982	$0	$2,036	-$2,036
1983	$0	$2,036	-$2,036
1984	$2,114	$2,036	$78
1985	$2,047	$2,036	$11
1986	$9,822	$2,036	$7,786
1987	$14,398	$1,639	$12,759
1988	$3,750	$1,335	$2,415
1989	$8,238	$1,015	$7,223
1990	$15,229	$1,025	$14,204
1991	$7,337	$2,277	$5,060
1992	$15,926	$3,542	$12,384
1993	$26,175	$3,745	$22,430

(continued)

[a] Total Benefits = conversion efficiency benefits [Column (g), Table 6-4)] + health benefits [Column (c), Table 6-8)]

Table 6-12. Net Benefits of Binary Cycle Power Plants Attributable to DOE, 1976–2008 (thousands $2008), (continued)

Year	Total Benefits[a]	Program Expenditures	Net Benefits
1994	$6,700	$3,770	$2,930
1995	-$12,363	$2,890	-$15,253
1996	-$5,514	$1,844	-$7,358
1997	$3,362	$1,925	$1,437
1998	$978	$1,787	-$809
1999	-$391	$1,616	-$2,007
2000	-$2,399	$1,452	-$3,851
2001	-$2,202	$1,203	-$3,405
2002	$2,226	$1,040	$1,186
2003	$2,489	$971	$1,518
2004	$1,721	$953	$768
2005	$6,471	$972	$5,499
2006	$4,882	$972	$3,910
2007	$2,677	$972	$1,705
2008	$10,533	$972	$9,561
Undiscounted Total	$124,206	$60,311	$63,893
PV[b] at 7%	**$42,848**	**$26,819**	**$16,029**
PV[b] at 3%	**$76,269**	**$40,701**	**$35,568**

[a] Total Benefits from Column (a-b), Table 6-11

[b] PV base year is 1976.

Table 6-13 summarizes the results of the benefit-cost analysis. In addition to net benefits with PV of $16.0 million discounted at 7%, the BCR is calculated to be 1.6 discounted at 7% (1.9 discounted at 3%). The BCR deceases at higher discount rates, reflecting the timing of expenditures and benefits. IRR serves as a measure of an investment's return by comparing initial investments with discounted cash flows. The IRR for binary cycle plant technology is 16%.

Table 6-13. Benefit-Cost Analysis Results

	Net Benefits	Benefit-Cost Ratio	Internal Rate of Return
PV[a] at 7%	$16,029	1.6	16%
PV[a] at 3%	$35,568	1.9	

[a] PV base year is 1976.

6.7 Sensitivity Analysis

When estimating the environmental health benefits, it was assumed that in the absence of geothermal electricity, additional gas, oil and coal-fired power plants would have been built to meet base load electricity demand. To investigate how sensitive our findings are to this assumption, this study estimated environmental health benefits from the binary cycle using an alternative assumption of 50% coal and 50% natural gas. The results are presented in Table 6-14. Using an assumption of 50% coal and 50% natural gas reduced the environmental health benefits by 15.9% or $3.6 million. This reduces the BCR ratio from 1.6 to 1.5.

Table 6-14. Binary Cycle Power Plants Environmental Benefits Attributable to DOE: Sensitivity to Displaced Fuel Type

	Displaced Generation		**Percentage Reduction**
	60% Coal, 39% NG, 1% Oil	**50% Coal, 50% NG**	
PM (short tons)	4,572	3,807	16.7%
SO_2 (short tons)	1,903	1,581	16.9%
NO_X (short tons)	998	838	16.0%
GHG (thousand tCO_2e)	1,319	1,254	4.9%
Monetized health benefit (PV[a] at 7%, thousands $2008)	$22,970	$19,323	15.9%

[a] PV base year is 1976.

7. TOUGH SERIES OF RESERVOIR MODELS: TECHNOLOGY IMPACT ASSESSMENT

7.1 Introduction

Reservoir modeling has become a widely practiced and accepted technique for studying flow and transport processes in subsurface flow systems. Reservoir modeling is used in many applications, including geothermal exploration and management, nuclear waste storage, and CO_2 sequestration. This section discusses the social benefits of reservoir modeling in general and the Transport of Unsaturated Groundwater and Heat (TOUGH) series of models (the leading family of reservoir modeling codes) in particular. This section also discusses DOE's role in the development and adoption of reservoir modeling in the United States. The PV of total benefits related to the TOUGH series of models is estimated to be approximately $954.1 million discounted at 7%. Approximately $219.4 million (PV discounted at 7%) of these benefits can be attributed to DOE through its research activities resulting from an investment with PV of $8.6 million (discounted at 7%).

7.2 History of the Technology

Initially, the geothermal industry's exploratory efforts were dominated by drilling near hot springs. As the industry expanded to take advantage of more challenging resources, there was a growing need for a better understanding of the characteristics of geothermal systems and the development of techniques to simulate systems in the subsurface. DOE's research efforts helped identify the limitations of traditional exploration techniques and demonstrate the potential for imaging and characterizing subsurfaces, which provided the foundation for geothermal reservoir modeling (EERE/GEO, 2008).

In general, reservoir models are used as analytical and management tools. As analytical tools, they are used in forecasting reservoir capacity, designing development activities, and identifying characteristics that may cause changes in the reservoir. Once a field is in operation and has accumulated data, reservoir modeling can then be used as a management and optimization tool. For example, modeling can be used to help position production and injection wells and to assist in optimizing the performance of the geothermal reservoirs by forecasting production scenarios and capacity of the field. Operating scenarios can also be modeled to help engineers better manage risk. A reservoir model can be used to estimate the long-term effects of shutting down individual wells on the entire field (Taylor, 2007).

The growth and development of reservoir modeling closely paralleled the development of an array of supporting technologies, such as advances in computer technology. Advances in computational power enabled numerical solutions to complex differential equations and supported early applications of reservoir modeling in the 1970s. However, the acceptance of computer simulation by the geothermal industry did not become widespread until in the 1980s, when DOE released its 1980 Code Comparison Study (O'Sullivan, 1980). In this paper, several models were tested, compared, and contrasted using a set of test problems. Since then, geothermal reservoir simulation codes have significantly improved and been widely accepted for geothermal applications, as well as other areas such as nuclear waste storage, mining engineering, and environmental restoration.

The use of computer simulation models in the planning and management stages of the development of geothermal fields has now been standard practice for more than two decades. Among the industry pioneers that introduced computer simulation code to a variety of applications were Lawrence Berkley National Laboratory (LBNL), Los Alamos National Laboratory (LANL), the United States Geological Service (USGS), GeothermEx, S-Cubed (which later became Maxwell Technologies), and Unocal (O'Sullivan et al., 2001).

Researchers at LBNL developed a simulation code known as MULKOM (multicomponent model). MULKOM was a first-of-a-kind, complex, three-dimensional model based on the assumption that governing equations for flows of multicomponent, multiphase liquids had the same mathematical structure regardless of the number and the nature of fluid components and phases. These efforts took place during the component development stage of the technology timeline. During the reservoir modeling system development stage, MULKOM served as a testing bed for methodologies and approaches that were later implemented in the TOUGH (released in 1987) and TOUGH2 (released in 1991) models. TOUGH is both an acronym for "transport of unsaturated groundwater and heat" and a reference to tuff formations in Yucca Mountain, which was one of the first major applications of the code (Pruess, 2004).

Subsequent versions of the TOUGH2 code focused on expanding beyond traditional application areas. T2VOC (released in 1995) and TMVOC (released in 2002) focused on environmental contamination problems of non-aqueous phase liquids. Inverse modeling, optimization, and sensitivity and uncertainty analysis were addressed with the iTOUGH2 code, which was released in 1999. TOUGHREACT (released in 2004) coupled TOUGH2 code with a general chemical speciation and reaction progress package. Finally, TOUGH-FLAC (not released to the public) coupled TOUGH2 with a commercial rock mechanics code, FLAC3D.[1] TOUGH2 and its offshoot codes are currently in use at approximately 300 installations in more than 30 countries (Pruess, 2004).

In addition to the TOUGH series of models, other entities were engaged in reservoir modeling activities in the 1980s and 1990s. Some of these were sponsored by the U.S. government (such as the Finite Element Heat and Mass Transfer Code (FEHM) at Los Alamos Laboratory), and others were conducted by the private sector. The two most prominent privately developed models were STAR and TETRAD.

STAR, developed at approximately the same time as TOUGH, geothermal simulation capabilities similar to TOUGH, but does not include the flexibility that makes TOUGH the leading research tool in the field. Initially, STAR was developed exclusively for geothermal applications; however, according to experts interviewed for this study, it has since been expanded to new areas, such as steam flood and CO_2 sequestration.

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[1] Release of the codes mentioned above was made through DOE's Energy Science and Technology Software Center (ESTSC).

TETRAD, developed several years after STAR and TOUGH, was created initially for oil and gas applications and has since been modified for geothermal applications (Taylor, 2007). Because TETRAD was applied to geothermal reservoir modeling later than TOUGH and STAR, its developers were able to draw from the best practices of those earlier models. Eventually, TETRAD became the main reservoir modeling software used for geothermal application in the United States. Industry experts interviewed as part of this study cited ease of use and a user-friendly interface as key selling points of TETRAD. In addition, a leading geothermal company at the time, Unocal Corporation, adopted TETRAD, creating a legacy of TETRAD usage that continues to this day.[2]

TOUGH's main advantage versus other reservoir modeling software is its flexibility. As one of the interview participants mentioned, one can reprogram TOUGH models to handle additional chemicals in a reservoir or to fit new applications. Some of the interview participants mentioned that a few fields started using other software, but are now switching back to TOUGH because of its flexibility.

Other advantages of TOUGH are that it is available for a small licensing fee, and continuously updated with enhancements from DOE and consultants who work with it. In general, the "publicness" of DOE's scientific efforts has enhanced commercial acceptance of the technology (Papadakis and Link, 1997). Since 1990, LBNL has held a series of TOUGH workshops and symposiums drawing together the international scientific community. Several interviewed experts acknowledged that the success of the TOUGH series models is tied to promotion of the code through publications, workshops, and symposia. These events and publications enhance collaboration between industry and the scientific community, helping to disseminate information, and providing a forum for advancing the TOUGH series models.

Table 7-1 presents a list of TOUGH series model workshops, their dates, attendance, and number of presentations. The first two workshops were held in 1990 and 1995 and focused on enhancements and additions to the TOUGH/MULKOM family of simulation programs.

Table 7-1. TOUGH Workshops

Workshop	Date	Participants	Presentations
1st TOUGH Workshop	September 1990	62	21
2nd TOUGH/MULKOM Workshop	March 1995	98	53
3rd TOUGH Workshop	May 1998	82	53
4th TOUGH Workshop	May 2003	81	62
5th TOUGH Workshop	May 15–17, 2006	90	60
6th TOUGH Workshop	September 14–16, 2009	124	89

Sources: Pruess (1995, 1998, 2009); LBNL (2009).

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[2] The experts interviewed suggested that the adoption of TETRAD by Unocal Corporation was also partially driven by concerns that use of DOE-sponsored software might be viewed as compromising the company's independence in terms of field valuation and decision making.

The 1990 workshop included 62 participants from seven different countries, with 21 papers presented on the following topics: geothermal reservoir engineering, nuclear waste isolation, unsaturated zone hydrology, environmental problems, and laboratory and field experimentation (Pruess, 1990). The 1995 workshop included nearly 98 participants from 10 countries, with 53 papers presented on nuclear waste isolation, geothermal and oil and gas reservoir engineering, mining engineering, simulation methods, vadose zone hydrology, and other topics (Pruess, 1995). The two most recent workshops were held in 2006 and 2009.

The 2006 workshop included 90 participants from more than 12 countries, with 60 papers presented (Oldenburg et al., 2007). The 2009 workshop included 124 participants, with 89 papers presented. In addition to the topics presented in the previous events, this meeting covered the additional topics of CO_2 storage and carbonate diagenesis. In addition to TOUGH technical conferences and symposia, LBNL has held many training courses over the years, in Berkeley and elsewhere.[3]

Following the market adoption of reservoir modeling technology, LBNL was responsible for maintaining the TOUGH code, implementing changes made both internally at the lab and externally by other researchers. Several interviewed experts noted that Berkeley has consistently helped resolve challenging programming inquiries. LBNL has also kept a record of errors and released new versions of the software as they became available.

Interviews also revealed that DOE and the TOUGH series of models have potentially had an even greater impact on geothermal industry outside the United States. A worldwide survey assessing the scope of and approaches to geothermal reservoir simulation studies (O’Sullivan et al., 2001) found that the TOUGH code was used in 48% of projects worldwide. The survey included 54 companies and individuals that documented 115 field simulations from 1990 to 1999. In contrast, TOUGH was used in approximately 5% of modeling activities in the United States during the same time period (O’Sullivan et al., 2001).

7.3 Next Best Alternative

Geothermal reservoir modeling is a new technology representing analysis capabilities of much higher complexity than previously available. The next best alternative technology is so-called “lumped parameter” models. These models were used before capabilities for detailed computer simulation of geothermal reservoirs were developed. They simplified the reservoir to a “zero dimensional tank” and then considered the effect of fluid production or injection on thermodynamic conditions. Lumped parameter models may have been adequate for estimating the cumulatively recoverable thermal energy for a system, but they provided limited information about how fast this energy could be recovered and how many production and injection wells would be required. These models similarly offered few clues as to where these wells should be located and at what rate makeup wells would be required as the reservoir

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[3] An example of these courses is the “Subsurface Multiphase Fluid Flow and Remediation Modeling” workshop, held in May 2006 for training T2VOC users. Most recently, four such courses were offered before and after the 2009 symposium.

was being depleted. This sometimes led to incorrect estimation of power plant capacity and increased installed cost (the Ohaki plant in New Zealand was mentioned as an example of this in the interviews).

7.4 Benefits Calculations

This section estimates the benefits associated with reservoir modeling in general.[4] Reservoir simulation provides both substantive and defensible analysis used to assess the productive capacity of a system, and the number and locations of production and injection wells. Industry experts identify two categories of benefits that can be quantified: (1) economic benefits resulting from increased field productivity of geothermal resources, valued at the market price of the additional electricity generated, and (2) the environmental benefits associated with the additional renewable energy offsetting fossil fuel generation. In addition, using reservoir modeling can reduce risk to investors, potentially accelerating and/or enabling geothermal developments; however, financing benefits are not included in the empirical analysis because they are difficult to document.

Note that these benefits are somewhat offset by additional exploration costs associated with reservoir modeling. Yet, when these factors are taken together, reservoir modeling can be said to have been profitable for the geothermal industry by improving subsurface exploration. Table 7-2 summarizes the key parameters and assumptions used to estimate benefits.

7.4.1 Economic Benefits

More efficient subsurface exploration improves well productivity by placing wells in the most efficient locations and leads to more optimal design for surface facilities. The increased productivity of geothermal reservoirs generates additional renewable energy.

Table 7-2. Key Parameters and Assumptions Used in the TOUGH Models Technology Benefits Analysis

Parameters/Assumptions	Source
Reservoir modeling has resulted in a 10% increase in field productivity	Empirical studies by Long (2008) and Renner (2009)
The use of reservoir modeling increased the cost of geothermal capacity by $160/kW	Empirical studies by Long (2008) and Aaheim and Bundschuh (2002)
Reservoir modeling was widely used in the geothermal industry by 1980	DOE released the 1980 Code Comparison Study (O'Sullivan, 1980) that showed the usefulness of reservoir modeling
Geothermal energy offsets fossil fuel-fired generation	60% coal, 39% natural gas, and 1% petroleum[5] (see Appendix C for calculations and sources)
The share of TOUGH usage for U.S. geothermal applications has historically been approximately 5%, with other reservoir models accounting for 95%	Study conducted by O'Sullivan (2001)

(continued)

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[4] Section 7.5 discusses what share of these benefits can be attributed to DOE's contribution through their development and dissemination of the TOUGH2 series of models.

[5] This is an average value of fuel mix across the states.

Table 7-2. Key Parameters and Assumptions and Used in the TOUGH Models Technology Benefits Analysis, (continued)

Parameters/Assumptions	Source
80% of benefits associated with using the TOUGH series of models attributed to DOE	Published literature, interviews with industry and DOE experts
20% of benefits associated with using other reservoir models attributed to DOE	Published literature, interviews with industry and DOE experts

Productivity Benefits

Productivity benefits are estimated by calculating the market value of the additional electricity generated as a result of using reservoir modeling. A Schlumberger report published in 2008 (Long, 2008) estimated that improvements in reservoir characterization have led to increases in well productivity in the oil and gas industry of up to 20%. No specific studies exist for geothermal reservoir modeling applications, but during our interviews with industry experts, several indicated substantial productivity benefits. They cited these models as essential for increasing productivity via well reinjections. In the California Geysers area, well reinjection has increased well productivity by approximately 10% (Renner, 2009). Therefore, this study assumes that reservoir modeling has resulted in a 10% increase in field productivity, a conservative estimate.

To estimate the additional MWh associated with the use of reservoir modeling, this study applied the 10% productivity increase to geothermal plants installed after 1980 – the approximate date geothermal reservoir modeling became standard practice.[6] As shown in Table 7-3, this yields an increase of 25.4 million MWh, which is valued at the average price of electricity over time to yield a total benefit with a PV of approximately $690.1 million discounted at 7%.

Table 7-3. Gain in Electricity Generated in the United States by the Geothermal Industry from the Use of TOUGH Models Technology

Year	*(a)* Price of MWh of Electricity, Including Taxes ($2008)[a]	*(b)* Geothermal Electricity Generated (MWh)[b]	*(c)* Adjusted Share of Electricity Generated Attributable to Reservoir Modeling[c] (MWh)	*(d)* Benefits Attributable to Reservoir Modeling (thousands $2008)[d]
1979	–	3,888,968	–	–
1980	$106.8	5,073,079	118,411	$12,646
1981	$114.2	5,686,163	179,720	$20,524
1982	$119.4	4,842,865	95,390	$11,390
1983	$118.6	6,075,101	218,613	$25,928
1984	$113.4	7,740,504	385,154	$43,676
1985	$113.5	9,325,230	543,626	$61,702
1986	$111.0	10,307,954	641,899	$71,251
1987	$106.7	10,775,461	688,649	$73,479
1988	$102.8	10,300,079	641,111	$65,906
1989	$100.7	14,593,443	1,070,448	$107,794
1990	$98.7	15,434,271	1,154,530	$113,952

(continued)

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[6] This study reports cost and benefits starting with 1980, which was the year that DOE released the 1980 Code Comparison Study (O'Sullivan, 1980) that showed the usefulness of reservoir modeling. Based on the results of the study, reservoir modeling was widely accepted by the geothermal industry, and the majority of reservoir software and modeling techniques were developed during the 1980s (O'Sullivan et al., 2001).

Table 7-3. Gain in Electricity Generated in the United States by the Geothermal Industry from the Use of TOUGH Models Technology, (continued)

Year	*(a)* Price of MWh of Electricity, Including Taxes ($2008)[a]	*(b)* Geothermal Electricity Generated (MWh)[b]	*(c)* Adjusted Share of Electricity Generated Attributable to Reservoir Modeling[c] (MWh)	*(d)* Benefits Attributable to Reservoir Modeling (thousands $2008)[d]
1991	$97.9	15,966,444	1,207,748	$118,238
1992	$96.7	16,137,962	1,224,899	$118,448
1993	$96.1	16,788,565	1,289,960	$123,965
1994	$93.9	15,535,453	1,164,649	$109,360
1995	$91.7	13,378,258	948,929	$87,017
1996	$89.6	14,328,684	1,043,972	$93,540
1997	$87.9	14,726,102	1,083,713	$95,258
1998	$85.5	14,773,918	1,088,495	$93,066
1999	$83.0	14,827,013	1,093,805	$90,786
2000	$83.3	14,093,158	1,020,419	$85,001
2001	$87.2	13,740,501	985,153	$85,905
2002	$84.8	14,491,310	1,060,234	$89,908
2003	$85.8	14,424,231	1,053,526	$90,393
2004	$85.3	14,810,975	1,092,201	$93,165
2005	$88.3	14,691,745	1,080,278	$95,389
2006	$93.5	14,568,029	1,067,906	$99,849
2007	$93.3	14,637,213	1,074,825	$100,281
2008	$98.2	14,859,238	1,097,027	$107,728
Undiscounted Total			25,415,288	2,385,545
PV[d] at 7%				**$690,113**

[a] Source: U.S. DOE (2009).
[b] Source: U.S. DOE (2010d).
[c] This column is calculated as follows (starting with year 1980) : (Column (b) Year$_t$ –Year$_{1979}$) x 10%.
[d] ((Column (a) x Column (c))/1000[e] Base year is 1976, which is the first year of DOE program expenses.

Increased Capital Costs

Additional exploration and modeling costs are associated with the use of reservoir modeling. The Schlumberger report (Long, 2008) estimates that reservoir modeling increased costs of exploration by approximately 20%. For geothermal power plants, Aaheim and Bundschuh (2002) estimated that depending on plant capacity, exploration costs constitute 10% to 30% of total capital costs. Thus, on average, this study assumes that exploration costs account for 20% of total capital costs. In addition, the Geothermal Energy Association estimated that 1 kW of installed plant capacity equates to approximately $4,000 in capital costs (GEA, 2009b).

From this it was calculated that the exploration costs per kW of power installed in a geothermal power plant as $4,000/kW × 20% = $800/kW, and the increase in cost per kW of using reservoir modeling as $800/kW × 20% = $160/kW.

The factor of $160/kW is then applied to incremental (new) geothermal capacity installed each year after 1980 to estimate the time series of industry reservoir modeling costs (see Table 7-4).[7] Incremental Installed plant capacity was calculated by subtracting cumulative plant capacity in the prior year from the cumulative capacity in the current year. Negative plant capacity installed meant that some plants were shut down and taken off the grid. It is assumed that the increase in capital costs in those years was zero. The PV of the industry cost related to reservoir modeling equaled $186.8 million discounted at 7%.

Table 7-4. Increase in Geothermal Exploration Costs in the United States due to TOUGH Models Technology, 1980–2008

Year	***(a)*** **Geothermal Plant Capacity[a] (MW)**	***(b)*** **Newly Installed Geothermal Plant Capacity[b] (kW)**	***((b) x $160/kW)*** **Increase in Capital Costs due to Reservoir Modeling (thousands $2008)**
1979	432	0	$0
1980	638	206,000	$32,960
1981	638	0	$0
1982	648	10,000	$1,600
1983	1,053	405,000	$64,800
1984	1,181	128,000	$20,480
1985	1,589	408,000	$65,280
1986	1,675	86,000	$13,760
1987	1,793	118,000	$18,880
1988	2,026	233,000	$37,280
1989	2,325	299,000	$47,840
1990	2,436	111,000	$17,760
1991	2,436	0	$0
1992	2,487	51,000	$8,160
1993	2,570	83,000	$13,280
1994	2,570	0	$0
1995	2,570	0	$0
1996	2,610	40,000	$6,400
1997	2,610	0	$0
1998	2,610	0	$0
1999	2,610	0	$0
2000	2,669	59,000	$9,440

(continued)

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[7] Note that the development of geothermal fields is frequently an ongoing process with an expanding and changing number of operational wells. The incremental costs associated with using simulation models are incurred throughout the development process of a field. This study uses incremental installed capacity coming on line each year to proxy for these capital costs. Admittedly, the more appropriate measure would be annual capital expenditures. However, this information is not available for the subset of geothermal power plants.

Table 7-4. Increase in Geothermal Exploration Costs in the United States due to TOUGH Models Technology, 1980–2008, (continued)

Year	***(a)*** **Geothermal Plant Capacity[a] (MW)**	***(b)*** **Newly Installed Geothermal Plant Capacity[b] (kW)**	***((b) x $160/kW)*** **Increase in Capital Costs due to Reservoir Modeling (thousands $2008)**
2001	2,669	0	$0
2002	2,669	0	$0
2003	2,669	0	$0
2004	2,669	0	$0
2005	2,699	30,000	$4,800
2006	2,756	57,000	$9,120
2007	2,771	15,000	$2,400
2008	2,818	47,000	$7,520
Undiscounted Total			$381,760
PV[c] at 7%			**$186,763**

[a] Source: GEA (2009a).
[b] Column calculated as follows: (Column (a) Year $_t$ – Column (a) Year $_{t-1}$).
[c] Base year is 1976, which is the first year of DOE program expenses.

7.4.2 Environmental Benefits

In the absence of reservoir modeling, the electricity generated due to improvement in geothermal productivity would have been otherwise generated by a mix of fossil fuels.[8] The resulting decrease in key criteria and GHG emissions are presented in Table 7-5 and represent the environmental benefits of reservoir modeling.

This study uses the U.S. Environmental Protection Agency's (EPA's) COBRA model to capture the monetary health benefits associated with the reduction in emissions. As described in Appendix C, the COBRA model uses changes in PM, NO_x, and SO_2 as inputs to estimate health impacts in terms of reductions in incidents. The reduction in incidents is then monetized using standard mortality, morbidity, and health care cost factors from the literature.

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[8] Generation from a mix of fossil fuels is used as the counterfactual if geothermal generation is removed because oil and gas are the primary electricity fuel source in the United States. Although the majority of geothermal plants are located in California, , California is a net importer of electricity from other states. It is assumed that in the absence of geothermal power generation, California would have increased power imports, which would have been supplied primarily by generation from a mix of fossil fuesl from neighboring states.

Table 7-5. TOUGH Models Technology Emission Reductions

Year	Electricity Generated Attributable to Reservoir Modeling[a] (MWh)	Particulates (short tons) SO_2 (short tons)	SO_2 (short tons)	NO_x (short tons)	CO_2 Equivalent Reduction[b] (thousand metric tons)
1980	118,411	357	156	82	107
1981	179,720	542	237	124	162
1982	95,390	288	126	66	86
1983	218,613	659	288	151	197
1984	385,154	1,161	508	266	347
1985	543,626	1,639	717	376	490
1986	641,899	1,935	847	444	578
1987	688,649	2,076	908	476	620
1988	641,111	1,933	846	443	578
1989	1,070,448	3,227	1,412	740	964
1990	1,154,530	3,480	1,523	798	1040
1991	1,207,748	3,641	1,593	835	1088
1992	1,224,899	3,692	1,616	846	1104
1993	1,289,960	3,889	1,701	891	1162
1994	1,164,649	3,511	1,536	805	1049
1995	948,929	2,861	1,252	656	855
1996	1,043,972	3,147	1,377	721	941
1997	1,083,713	3,267	1,429	749	976
1998	1,088,495	3,281	1,436	752	981
1999	1,093,805	3,297	1,443	756	985
2000	1,020,419	3,076	1,346	705	919
2001	985,153	2,970	1,299	681	888
2002	1,060,234	3,196	1,398	733	955
2003	1,053,526	3,176	1,390	728	949
2004	1,092,201	3,292	1,441	755	984
2005	1,080,278	3,257	1,425	746	973
2006	1,067,906	3,219	1,409	738	962
2007	1,074,825	3,240	1,418	743	968
2008	1,097,027	3,307	1,447	758	988
Total		**76,615**	**33,523**	**17,561**	**22,897**

[a] Column (c) in Table 7-3.

[b] Calculation based on Electricity Generated Attributable to Reservoir Modeling (a) and Carbon Dioxide Emission Rates: Coal 2.117; Natural Gas 1.314; Oil 1.915 pounds per KWh (U.S. DOE, 2010c).

The results from the model are presented in Table 7-6. Total annual health effects in 2008 are valued at \$81.6 million, with the majority of the benefits coming from avoided mortality.[9] For a detailed discussion of the environmental benefits calculation, refer to Appendix C.

Table 7-6. Annual Health Impacts of TOUGH Models Technology, 2008 (thousands \$2008)

Health Risks	Reduction in Incidents	Decrease in Costs (thousands \$2008)
Mortality	12	\$75,000
Infant mortality	0	\$230
Chronic bronchitis	8	\$3,564
Nonfatal heart attacks	17	\$1,890
Respiratory hospital admissions	2	\$30
Cardiovascular-related hospital admissions	5	\$134
Acute bronchitis	20	\$8
Upper respiratory symptoms	178	\$5
Lower respiratory symptoms	237	\$4
Asthma emergency room visits	7	\$2
Minor restricted activity days	9,939	\$605
Work days lost	1,680	\$134
Total Health Effects	**12,105**	**\$81,606**

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[9] The mean value for avoiding one statistical death in the COBRA model is \$5.5 million (\$2000) (USEPA, 2006).

The 2008 health impacts are then scaled by historical population and geothermal capacity in place to generate a time series of health benefits (see Table 7-7).

Table 7-7. Environmental Health Benefits of TOUGH Models Technology, 1980–2008

Year	U.S. Population [a]	*(b)* Adjusted Share of Electricity Generated Attributable to Reservoir Modeling[b] (MWh)	*(c)* Environmental Health Benefits Attributable to Reservoir Modeling[c] (thousands $2008)
1980	227,224,681	118,411	$6,583
1981	229,465,714	179,720	$10,089
1982	231,664,458	95,390	$5,406
1983	233,791,994	218,613	$12,504
1984	235,824,902	385,154	$22,221
1985	237,923,795	543,626	$31,643
1986	240,132,887	641,899	$37,711
1987	242,288,918	688,649	$40,820
1988	244,498,982	641,111	$38,349
1989	246,819,230	1,070,448	$64,638
1990	249,464,396	1,154,530	$70,463
1991	252,153,092	1,207,748	$74,505
1992	255,029,699	1,224,899	$76,425
1993	257,782,608	1,289,960	$81,353
1994	260,327,021	1,164,649	$74,175
1995	262,803,276	948,929	$61,011
1996	265,228,572	1,043,972	$67,742
1997	267,783,607	1,083,713	$70,998
1998	270,248,003	1,088,495	$71,967
1999	272,690,813	1,093,805	$72,972
2000	282,171,936	1,020,419	$70,443
2001	285,039,803	985,153	$68,700
2002	287,726,647	1,060,234	$74,632
2003	290,210,914	1,053,526	$74,801
2004	292,892,127	1,092,201	$78,263
2005	295,560,549	1,080,278	$78,114
2006	298,362,973	1,067,906	$77,951
2007	301,290,332	1,074,825	$79,226
2008	304,059,724	1,097,027	$81,606
Undiscounted Total			$1,675,314
PV[d] at 7%			**$450,758**

[a] Source: U.S. Bureau of Census (2000, 2009).

[b] Column (c) from Table 7-3.

[c] Health Benefits in 2008 [$81.6 Million from Table 7-6] scaled by Column (a) and Column (b)

[d] Base year is 1976, which is the first year of DOE program expenses.

The PV of the health benefits from 1980 through 2008 (base year 1976) is calculated to be $450.8 million discounted at 7%.

7.4.3 Security Benefits

Security benefits derive from reducing the probability and potential impact of oil and natural gas disruptions and price shocks or other energy system disruptions that would damage or disrupt the economy, environment, or national security of the United States. These benefits are realized through substitution of a volume of oil and natural gas, which otherwise would be combusted to produce electricity, with geothermal electricity generation technology. Table 7-8 presents the reduction in 19.4 billion cubic feet of natural gas or 3.4 million barrels of oil equivalent.

Table 7-8. Security Benefits of TOUGH Models Technology Attributable to DOE, 1980–2008

Year	MWh[a]	Million Cubic Feet of Natural Gas[b]	BOE (Thousand Barrels of Oil Equivalent)[b]
1980	118,411	90	16
1981	179,720	137	24
1982	95,390	73	13
1983	218,613	167	30
1984	385,154	294	52
1985	543,626	415	74
1986	641,899	490	87
1987	688,649	526	93
1988	641,111	489	87
1989	1,070,448	817	145
1990	1,154,530	881	156
1991	1,207,748	922	163
1992	1,224,899	935	166
1993	1,289,960	985	175
1994	1,164,649	889	158
1995	948,929	724	128
1996	1,043,972	797	141
1997	1,083,713	827	147
1998	1,088,495	831	147
1999	1,093,805	835	148
2000	1,020,419	779	138
2001	985,153	752	133
2002	1,060,234	809	143
2003	1,053,526	804	143
2004	1,092,201	834	148
2005	1,080,278	825	146
2006	1,067,906	815	144
2007	1,074,825	820	145
2008	1,097,027	837	148
Total	**25,415,288**	**19,401**	**3,438**

[a] Column (c) from Table 7-3.

[b] DOE Attribution was applied by multiplying million cubic feet of natural gas or BOE by the attribution factor, 23% [Table 7-11 discounted total-benefits attributable to DOE/ discounted total reservoir modeling benefits]

7.4.4 Total Benefits

Finally, the total benefits of reservoir modeling were calculated by adding productivity and environmental health benefits and subtracting additional modeling costs. This calculation is presented in Table 7-9. The PV of the total benefits of reservoir modeling to the geothermal industry equaled $954.1 million discounted at 7%.

Table 7-9. Total Benefits of TOUGH Models Technology in the Geothermal Industry in the United States, 1980–2008 (thousands $2008)

Year	Productivity Benefits Attributable to Reservoir Modeling[a]	Environmental Health Benefits Attributable to Reservoir Modeling[b]	Increase in Capital Costs due to Reservoir Modeling	*(d)* Total Reservoir Modeling Benefits
1980	$12,646	$6,583	$32,960	-$13,731
1981	$20,524	$10,089	$0	$30,613
1982	$11,390	$5,406	$1,600	$15,196
1983	$25,928	$12,504	$64,800	-$26,368
1984	$43,676	$22,221	$20,480	$45,418
1985	$61,702	$31,643	$65,280	$28,065
1986	$71,251	$37,711	$13,760	$95,201
1987	$73,479	$40,820	$18,880	$95,419
1988	$65,906	$38,349	$37,280	$66,975
1989	$107,794	$64,638	$47,840	$124,592
1990	$113,952	$70,463	$17,760	$166,655
1991	$118,238	$74,505	$0	$192,744
1992	$118,448	$76,425	$8,160	$186,713
1993	$123,965	$81,353	$13,280	$192,039
1994	$109,360	$74,175	$0	$183,536
1995	$87,017	$61,011	$0	$148,028
1996	$93,540	$67,742	$6,400	$154,881
1997	$95,258	$70,998	$0	$166,256
1998	$93,066	$71,967	$0	$165,034
1999	$90,786	$72,972	$0	$163,758
2000	$85,001	$70,443	$9,440	$146,004
2001	$85,905	$68,700	$0	$154,605
2002	$89,908	$74,632	$0	$164,540
2003	$90,393	$74,801	$0	$165,193
2004	$93,165	$78,263	$0	$171,428
2005	$95,389	$78,114	$4,800	$168,702
2006	$99,849	$77,951	$9,120	$168,681
2007	$100,281	$79,226	$2,400	$177,107
2008	$107,728	$81,606	$7,520	$181,814
Undiscounted Total	$2,385,545	$1,675,314	$381,760	$3,679,098
PV[c] at 7%	**$690,113**	**$450,758**	**$186,763**	**$954,108**

[a] Column (d) from Table 7-3.

[b] Column (c) from Table 7-7.

[c] Base year is 1976, which is the first year of DOE program expenses.

This study was unable to quantify non-geothermal applications of the TOUGH series of models in this analysis. Reservoir modeling has been adapted for other uses, such as nuclear waste storage and CO_2 sequestration, and for these applications, the TOUGH model has been the primary modeling tool. Thus, this study presents a conservative retrospective estimate of the economic impact of this family of reservoir models.

7.5 Attribution Share

Section 7.4 estimated the economic and environmental impact of reservoir models used for geothermal application. This section assesses the share of these benefits that can be attributed to DOE's development and dissemination of the TOUGH series of reservoir models. To assess the share of benefits attributable to the TOUGH series reservoir models, Table 7-10 presents a historic timeline of DOE's and other organizations' involvement with the development, demonstration, commercialization, and adoption of geothermal reservoir models.

Before 1975, reservoir modeling was used for large-scale oil and gas reservoir applications, but computational power was costly and models were not designed to handle the more complex temperature and pressure characteristics of geothermal fields. Thus, DOE's activities in the late 1970s and early 1980s were at the forefront of geothermal reservoir model development, and coincided with the evolution of computer capabilities that enabled complex simulation models to be run cost-effectively.

To quantify attribution, this study sought to partition the suite of available reservoir models into two groups: (1) the TOUGH series of models, and (2) other reservoir models (e.g., TETRAD, STAR). It was assumed that the net benefits of using reservoir models (quantified in Section 7.4) are approximately the same for both groups. Industry experts interviewed as part of the study indicated that the fundamentals of most geothermal reservoir models are similar, and that for most applications, the leading models are comparable. Model selection was historically based more on familiarity with specific models (legacy use) rather than unique modeling capabilities and benefits. Yet, experts indicated that they expect the use of the TOUGH series of models to increase in the future because of the flexibility of the TOUGH models to simulate more diverse and complicated applications such as carbon sequestration and groundwater contamination.

The DOE attribution between the two groups is different:

- DOE had overwhelming influence (80%) on the TOUGH series models.
- DOE efforts were influential (20%) on other reservoir models.

Table 7-10. A Matrix for Assessing DOE Attribution of the TOUGH Models Technology by Stage

Categories of Information Needed for Additionality Assessment	**Technology Timeline (Stage of Research, Development, and Commercialization)→**						
	Preliminary & Detailed Investigation	**Develop Components**	**Develop System**	**Validate/ Demonstrate**	**Commercialize**	**Market Adoption**	**DOE Attribution**
What DOE did	▪ Identified limitations of exploration techniques and potential for imaging subsurface ▪ Organized 1980 Code Comparison Study	▪ MULKOM model developed	▪ MULKOM served as a testing bed for TOUGH and TOUGH2	▪ Held a series of workshops and symposia, which enhanced collaborations between commercial and scientific communities	▪ TOUGH code is distributed through DOE website	▪ LBNL maintains, distributes, and adds to the code ▪ TOUGH is widely used around the world	80% of benefits attributed to DOE for modeling using TOUGH series
What others did		▪ STAR developed by S-Cubed	▪ TETRAD developed		▪ TETRAD became a primary software used for geothermal application in the United States		
Driving forces	▪ More powerful computers are developed allowing for more sophisticated programming				▪ Unocal Corporation chooses TETRAD as non-DOE-sponsored technology		
Description of DOE influence	▪ **Overwhelming (90%)** ▪ Industry was at the inception, and DOE demonstrated validity of reservoir modeling	▪ **Overwhelming (100%)** ▪ One of the first models to use computing power to build an operational model	▪ **Overwhelming (100%)** ▪ DOE compiled best practices and state of modeling; introduced first-of-a-kind implicit approach	▪ **Overwhelming (90%)** ▪ DOE encouraged collaboration and publication of best practices	▪ **Very important (50%)** ▪ DOE provided some support to stakeholders that have chosen to run TOUGH	▪ **Very important (50%)** ▪ DOE maintains and updates the code, as some companies are switching to TOUGH because of its flexibility	

(continued)

Table 7-10. A Matrix for Assessing DOE Attribution of the TOUGH Models Technology by Stage, (continued)

Categories of Information Needed for Additionality Assessment	**Technology Timeline (Stage of Research, Development, and Commercialization)→**						
	Preliminary & Detailed Investigation	**Develop Components**	**Develop System**	**Validate/ Demonstrate**	**Commercialize**	**Market Adoption**	**DOE Attribution**
Basis of evidence for influence ▪ Public record, patent citations ▪ Interviews with third parties ▪ Interviews with partners ▪ Other	▪ Attendance at DOE conferences and DOE publications	▪ Interviews with partners ▪ Interviews with third parties	▪ Interviews with partners ▪ Interviews with third parties	▪ Other – research			80% of benefits attributed to DOE for modeling using TOUGH Series
The DOE effect	▪ Accelerated technology entry	▪ Accelerated technology entry	▪ Improved performance	▪ Improved performance	▪ Improved performance ▪ Increased market size internationally	▪ Improved performance ▪ Increased market size internationally	
The DOE effect	▪ Accelerated technology entry	▪ Accelerated technology entry	▪ Improved performance	▪ Improved performance	▪ Improved performance ▪ Increased market size internationally	▪ Improved performance ▪ Increased market size internationally	

Based on a study conducted by O'Sullivan (2001), the share of TOUGH usage for U.S. geothermal applications has historically been approximately 5%, with other reservoir models accounting for 95% of U.S. geothermal reservoir modeling. Using these usage shares and the attribution rates, this study calculated PV of total benefits attributable to DOE to be $219.4 million discounted at 7% for the period 1980 to 2008 (see Table 7-11).

Table 7-11. Benefits of TOUGH Models Technology Attributable to DOE, 1980–2008

Year	***(a): (Column (d) from Table 7-9)*** **Total Reservoir Modeling Benefits**	**TOUGH Model Benefits Attributable to DOE (80%)**	**Other Model Benefits Attributable to DOE (20%)**	***(b) + (c)*** **Total DOE Benefits (thousands $2008)**
		(b): (a) * 80% * 5% **5% of All Reservoir Models**	***(c): (a) * 20% * 95%*** **95% of All Reservoir Models**	
1980	-$13,731	-$549	-$2,609	-$3,158
1981	$30,613	$1,225	$5,817	$7,041
1982	$15,196	$608	$2,887	$3,495
1983	-$26,368	-$1,055	-$5,010	-$6,065
1984	$45,418	$1,817	$8,629	$10,446
1985	$28,065	$1,123	$5,332	$6,455
1986	$95,201	$3,808	$18,088	$21,896
1987	$95,419	$3,817	$18,130	$21,946
1988	$66,975	$2,679	$12,725	$15,404
1989	$124,592	$4,984	$23,673	$28,656
1990	$166,655	$6,666	$31,664	$38,331
1991	$192,744	$7,710	$36,621	$44,331
1992	$186,713	$7,469	$35,475	$42,944
1993	$192,039	$7,682	$36,487	$44,169
1994	$183,536	$7,341	$34,872	$42,213
1995	$148,028	$5,921	$28,125	$34,046
1996	$154,881	$6,195	$29,427	$35,623
1997	$166,256	$6,650	$31,589	$38,239
1998	$165,034	$6,601	$31,356	$37,958
1999	$163,758	$6,550	$31,114	$37,664
2000	$146,004	$5,840	$27,741	$33,581
2001	$154,605	$6,184	$29,375	$35,559
2002	$164,540	$6,582	$31,263	$37,844
2003	$165,193	$6,608	$31,387	$37,994
2004	$171,428	$6,857	$32,571	$39,428
2005	$168,702	$6,748	$32,053	$38,802
2006	$168,681	$6,747	$32,049	$38,797
2007	$177,107	$7,084	$33,650	$40,735
2008	$181,814	$7,273	$34,545	$41,817
Undiscounted Total	$3,679,098	$147,164	$699,029	$846,193
PV[a] at 7%	**$954,108**	**$38,164**	**$181,280**	**$219,445**

[a] PV base year is 1976.

7.6 Benefit-Cost Analysis

DOE program expenditures associated with the TOUGH family of reservoir models are presented in Table 7-12. These expenditures are based on appropriation items provided by DOE for EERE budgets from 1976 to 2008. The expenditures in Table 7-12 are built up from the number of full-time equivalents (FTEs) spent on developmental work associated with the TOUGH models, and they represent approximately 0.1% of EERE's total GTP budget during this time period (Pruess, 2009). The PV of total expenditures (adjusted to $2008) equaled $8.6 million discounted at 7% from 1976 to 2008. DOE's investment in the TOUGH models yielded net benefits with PV of $210.8 million discounted at 7% ($446.3 million discounted at 3%).

Table 7-12. Net Benefits of TOUGH Models Technology Attributable to DOE, 1976–2008 (thousands $2008)

Year	Total Benefits	Expenses	Net Benefits
1976	$0	$797	-$797
1977	$0	$797	-$797
1978	$0	$797	-$797
1979	$0	$797	-$797
1980	-$3,158	$797	-$3,955
1981	$7,041	$797	$6,244
1982	$3,495	$797	$2,698
1983	-$6,065	$797	-$6,862
1984	$10,446	$797	$9,649
1985	$6,455	$797	$5,658
1986	$21,896	$797	$21,099
1987	$21,946	$797	$21,149
1988	$15,404	$797	$14,607
1989	$28,656	$797	$27,859
1990	$38,331	$797	$37,534
1991	$44,331	$797	$43,534
1992	$42,944	$159	$42,785
1993	$44,169	$159	$44,010
1994	$42,213	$159	$42,054
1995	$34,046	$159	$33,887
1996	$35,623	$159	$35,464
1997	$38,239	$159	$38,080
1998	$37,958	$159	$37,799
1999	$37,664	$159	$37,505
2000	$33,581	$159	$33,422
2001	$35,559	$159	$35,400
2002	$37,844	$159	$37,685
2003	$37,994	$159	$37,835
2004	$39,428	$159	$39,269
2005	$38,802	$159	$38,643
2006	$38,797	$159	$38,638
2007	$40,735	$159	$40,576
2008	$41,817	$159	$41,658
Undiscounted Total	$846,193	$15,462	$831,670
PV[a] at 7%	**$219,445**	**$8,619**	**$210,826**
PV[a] at 3%	**$457,957**	**$11,655**	**$446,302**

[a] PV base year is 1976.

Table 7-13 summarizes the results of the benefit-cost analysis. In addition to net benefits with PV of $210.8 million discounted at 7%, the ratio of benefit attributed to DOE expenditures was calculated (referred to as the BCR). The BCR decreases at higher discount rates, reflecting the timing of expenditures and benefits. The BCR (discounted at 7%) equaled 25.5 (39.3 discounted at 3%). The IRR serves as a measure of an investment's return by comparing initial investments with discounted cash flows. The IRR for the TOUGH program was 48%.

Table 7-13. Benefit-Cost Analysis Results

	Net Benefits (thousands $2008)	Benefit-Cost Ratio	Internal Rate of Return
PV[a] at 7%	$210,826	25.5	48%
PV[a] at 3%	$446,302	39.3	

[a] PV base year is 1976.

7.7 Sensitivity Analysis

When estimating the environmental health benefits, it was assumed that in the absence of geothermal electricity, additional oil, gas and coal-fired power plants would have been built to meet base load electricity demand. To investigate how sensitive our findings are to this assumption, this study estimated environmental health benefits from TOUGH series of models using an alternative assumption of 50% coal and 50% natural gas. The results are presented in Table 7-14. Using an assumption of 50% coal and 50% natural gas reduced the environmental health benefits by 14.9% or $15.5 million. This reduces the BCR for the TOUGH series of models from 25.5 to 23.7.

Table 7-14. TOUGH Models Technology Benefits Attributable to DOE: Sensitivity to Displaced Fuel Type

	Displaced Generation[a]		Percentage Reduction
	60% Coal, 39% NG, 1% Oil	50% Coal, 50% NG	
PM (short tons)	17,621	14,973	15.0%
SO_2 (short tons)	7,710	6,410	16.9%
NO_X (short tons)	4,039	3,389	16.1%
GHG (thousand tCO_2e)	5,266	5,014	4.8%
Monetized health benefit (PV[a] at7%, thousands $2008)	$103,674	$88,178	14.9%

[a] PV base year is 1976.

8. HIGH-TEMPERATURE CEMENT: TECHNOLOGY IMPACT ASSESSMENT

8.1 Introduction

In the late 1970s, DOE's GTP set out to develop new enabling technologies that would lower the costs of geothermal energy production and expand our ability to capture and fully utilize this sustainable energy resource. Early geothermal energy projects revealed that the use of Portland cement in geothermal wells was problematic, leading to frequent and costly repairs and significantly shorter well lifetimes. For this reason, DOE began funding basic research on well cements with the long-term goal of applying this research to the development of new well cements that address the shortcomings of existing Portland cements in geothermal wells. Over the next 30 years, DOE funded Brookhaven National Laboratory's (BNL's) basic materials research and applied research on the cementitious properties of various chemical formulations. BNL's research led to the patenting and commercialization of a calcium aluminate phosphate (CaP) cement system that is resistant to acidic corrosion and maintains structural integrity at extremely high temperatures.

The following sections detail the historical events leading to the development of high-temperature cement; identifies the alternative technology scenario; values the benefits of the technology and determines the proportion of the benefits attributable to DOE; and concludes with a benefit-cost ratio estimate computed for high-temperature cement.

8.2 History of the Technology

Accessing geothermal resources deep beneath the Earth's surface requires drilling wells to depths typically greater than 1,000 meters, with some projects requiring deeper wells that can exceed 5,000 meters (Augustine et al., 2006). The harsh environmental conditions at these depths have presented numerous challenges to geothermal projects in terms of well construction and long-term stability.

Portland cement has long been used in well completions for cementing in place the steel casing that lines the inside of the well borehole. The cement and casing combined prevent well borehole collapse and maintain well pressure. The American Petroleum Institute Specification 10A defines the standards for oil and gas well cementing (Bensted, 1998). The Institute's standard specifies eight classes of Portland cements commonly used in the oil and gas industry.

Although Portland cement continues to be the industry standard for most oil and gas wells, it has proven problematic for use in geothermal wells, deep oil and gas wells, and steam and CO_2 injection wells due to the harsh environmental conditions characterized by extremely high temperatures, high concentrations of CO_2, and acidic sulfuric acid (H_2SO_4) brine ($pH < 1.5$) (U.S. DOE, 2005a).

A 2006 report by BNL lead scientist Toshifumi Sugama identifies two major regions of geothermal wells that are particularly susceptible to cementing failures: the "deep hot downhole area (~1,700 m depth at temperature ~320^oC)" and the "upper well region consisting of the area between the surface and ~1000 m depth at temperatures ~200^oC" (Sugama, 2006). Sugama explains that when placed in these environments, Portland cement's chemical composition reacts with "hot CO_2 and H_2SO_4" causing rapid deterioration of the cement's structural integrity and increased porosity due to acidic erosion, allowing acidic brine to permeate and accelerating corrosion of the steel casing. The cement deterioration leads to impaired performance or complete failure of a geothermal well, typically within one year. In more severe cases wells collapsed in less than 3 months (Sugama, 2006). This leads to costly well remediation, including redrilling and recementing failed wells (U.S. DOE, 2005a). See Chapter 9 for discussion of patents and knowledge benefits.

Between 1994 and 2006, BNL conducted R&D work to address the cement issues with a stated goal of reducing well drilling and reservoir management costs by 25% (Sugama, 2006). The BNL research team worked to develop novel alternative cements that would resist CO_2 and acidic brine at higher temperatures (up to 320^oC). This research program succeeded in developing two novel cements, CaP and sodium silicate-activated slag (SSAS) (Sugama, 2006).

CaP is a non-Portland–based cement composed of calcium aluminate cement, sodium polyphosphate, Class F fly ash, and water. CaP cements demonstrated resistance to high concentrations of CO_2 in downhole environments with low acidity levels (pH ~5.0) (Sugama, 2006). SSAS is also a non-Portland–based cement composed of slag, Class F fly ash, sodium silicate, and water. SSAS was designed to be heat tolerant and to resist strong acids with low concentrations of CO_2 (Sugama, 2006).

In 1997, Unocal and Halliburton field tested the CaP cement formulation, using it in the completion of four geothermal wells in northern Sumatra and Indonesia (Sugama, 2006). In parallel with the field tests, BNL conducted an in-house exposure test to monitor the integrity of the cement over a period of seven months in environmental conditions that mirrored those found in the Indonesian wells (~20,000 ppm CO_2, and 400 ppm hydrogen sulfide at 280^oC) (Sugama, 2006). Results of the BNL exposure test confirmed that the cement demonstrated excellent durability in the extreme environments of geothermal wells (Sugama, 2006).

In 1999, only two years after field testing, Halliburton commercialized CaP cement under the trade name ThermaLock which has since been used in a number of international and domestic geothermal well completion projects (Sugama, 2006). The applications of ThermaLock extend beyond geothermal wells to uses in enhanced oil recovery applications for cementing of CO_2, steam, and sour-gas re-injection wells; and deep sea offshore oil recovery in the North Sea (Sugama, 2006; U.S. DOE, 2005a).

The BNL-developed cement commercialized under the trade name ThermaLock has the potential to extend the life expectancy of geothermal wells by 20 years, mitigating the need for frequent and costly well remediation (Sugama, 2006). This technology lowers maintenance costs over the life of the geothermal well; however, it increases initial costs due to special requirements for handling equipment and cementing expertise. Although the total NPV is positive, the up-front increased well completion costs have been a barrier to widespread adoption of ThermaLock by geothermal energy projects in the United States.

Halliburton is the only supplier of ThermaLock and is also the leading supplier of Portland cement for geothermal wells. However, there is no evidence that market structure (power) has influenced the slow penetration of ThermaLock. Halliburton views this product as having higher potential profitability compared with Portland cement because of its higher value added in the manufacturing process. The commonly cited barrier to adopting ThermaLock is the higher upfront capital costs and asymmetric incentives between developers wanting to bring geothermal plants online at the lowest initial investment costs and owners that would benefit from the lowest life-cycle costs. Availability and cost of capital are also cited by industry as reasons for minimizing upfront capital costs.

8.3 Next Best Alternative

High-temperature well cement is an example of a technology improvement. The next best alternative technology is the traditional Portland-based well cements commonly used in geothermal, oil, and gas wells. Originally developed for use in geothermal wells, high-temperature cement has also been used for enhanced oil recovery projects and offshore well drilling. The DOE-developed cement technology impacts new well construction and ongoing maintenance at high-temperature geothermal production wells. The DOE-developed cement is expected to have similar impacts on CO_2, steam, and sour-gas re-injection wells at enhanced oil recovery projects as well as in deep sea offshore oil recovery in the North Sea.

Portland-based cement blends are used for well construction and maintenance to ensure structural integrity of the well borehole and steel casing, and to ensure adequate internal pressure; however, exposure to extremely high temperatures can lead to cracking and buckling of the cement sheath. In addition, Portland cements are susceptible to corrosion by carbonic acid formed from water saturated with CO_2 (Brothers, 2006). Exposure to high temperatures and highly acidic solutions in geothermal brines compromises Portland cement’s physical properties and can result in cement sheath cracking, buckling, and corrosion (Berard et al., 2009; Sugama, 2006).

The rapid deterioration of Portland cement in geothermal wells (<12 months) resulted in frequent well workovers[1] and costly well remediation (U.S. DOE, 2005a). The use of high-temperature cements enhances performance in terms of structural stability and corrosion resistance and is estimated to eliminate $150,000 in annual well remediation costs and extend the working life of geothermal

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[1] Well workovers are defined as repair or maintenance activities on an existing well intended to extend the useful life of the well (Schlumberger, 2009).

production wells to 20 years or more (Sugama, 2006). These estimates were confirmed through interviews with industry experts.

Despite enhanced performance characteristics, the geothermal industry has been slow to adopt ThermaLock, due in large part to its significantly higher initial costs compared to traditional Portland cements. Using ThermaLock for a cementing job is likely to cost twice as much as the same job using conventional Portland cement. ThermaLock's higher costs are largely the result of specialized equipment and expertise required to handle this product. For example, contamination of ThermaLock with Portland cement will result in a chemical reaction that drastically reduces the pumping time before the cement begins to set up. Avoiding this problem requires segregated transportation and pumping equipment, as well as specialized expertise to handle the cement.

8.4 Benefits Calculations

The economic benefits obtained through DOE's development of high-temperature cements can be separated into two categories: (1) cost savings to the end users of CaP cement, and (2) increased profits attributable to the cement manufacturing company. End users include geothermal operators and oil/gas producers that used the ThermaLock cement in well completions and casing repairs. Table 8-1 summarizes the key parameters and assumptions used to estimate benefits.

Table 8-1. Key Parameters and Assumptions Used in the High-Temperature Cement Benefits Analysis

Parameters/Assumptions	Source
Life-cycle costs for a prototypical well by application and cement type	U.S. DOE (2005a), U.S. DOE (2007), Augustine et al. (2006), and interviews with well cementing service industry experts.
ThermaLock wells have a 20-year life expectancy. Wells with Portland cement are reworked every 5 years.	Author interviews with well cementing service industry experts.
Manufacturers' profit margin of 6.8%	Corporate Income and Profitability for Support Activities for Mining (NAICS 2131110), IRS (2008)
48% of benefits associated with ThermaLock applications are attributed to DOE	Published literature, interviews with industry and DOE experts

8.4.1 Economic Benefits from Corporate Profits

Estimating the sales revenue realized by the cement manufacturer is a relatively straightforward task, given that the CaP cement technology was commercialize by a single company. Halliburton commercialized CaP cement as ThermaLock in February 1999 and in the same year exported ~116 tons of the cement to Japan for use in two major steam producing – well completion projects conducted by the Japanese energy company JAPEX (U.S. DOE, 2000b). In April of 2000, JAPEX purchased an additional 60 tons for other geothermal well completions (U.S. DOE, 2000b). By July 2006, Halliburton had sold more than 1,000 tons of ThermaLock cement for geothermal and oil recovery applications around the globe (Sugama, 2006).

Benefits from increased taxable sales revenue were developed by estimating the share of company profits attributable to ThermaLock cementing services between 1999 and 2007. Halliburton's annual financial reports do not disclose sales at this level of detail. Therefore, this study estimated a time series of sales revenue based on information obtained in interviews with Halliburton combined with published case studies on projects that used ThermaLock. The time series revenue estimates include ThermaLock cementing services provided to both domestic and international customers, because all profits accrue to the U.S. division of Halliburton.

Annual corporate income and profitability data published by the Internal Revenue Service (IRS) were used to calculate a before-tax profit margin for the Support Activities for Mining (NAICS 2131110), which includes Halliburton. Table 8-2 reports the profit margin calculated from the IRS data for 2004 through 2006.

Table 8-2. Corporate Income and Profitability for Support Activities for Mining (NAICS 2131110)

Value Description	2004	2005	2006
Number of corporations	6,481	7,866	9,059
Number of corporations with net income	4,264	5,075	7,275
Total receipts (thousands $)	$49,983,340	$64,294,768	$84,474,588
Business receipts (thousands $)	$45,546,332	$60,774,902	$79,060,261
Before-tax profit margin	6.57%	7.17%	20.61%
After-tax profit margin	5.68%	5.02%	15.90%

Source: IRS (2008).

After reviewing IRS data for the 3-year period, a before-tax profit margin of 6.87% was chosen as a representative ratio, calculated as the before-tax income divided by total business receipts for 2004 and 2005. Starting in 2006, the mining support service industry's profit margins quadrupled, closely following a dramatic rise in oil prices that signaled a sudden shift in demand for mining support services from the oil producers. For this reason, the analysis omits the 2006 profit margin estimates. This represents a conservative estimate of Halliburton's profit margins, given that it is one of the largest firms in the support activities for mining industry.

The benefits estimation methodology assumes that profits associated with ThermaLock would be similar to other products and services provided by Halliburton. Hence, the analysis applies the average profit margin to a historical time series of ThermaLock sales for 1999 to 2008.

The profit ratio of 6.87% was multiplied by the annual sales of ThermaLock in each year to estimate the before-tax profits Halliburton realized from the product line since its commercialization. Table 8-3 presents the sales and net profits estimated in 2008 dollars.

Table 8-3. Manufacturer Profits from High-Temperature Cement Technology, 1999–2008

Year	No. of Cemented Wells		Annual Sales (thousands $current)	Before-Tax Profits (thousands $current)	Before-Tax Profits (thousands $2008)
	International	Domestic			
1999	2	0	$1,000	$69	$86
2000	1	2	$786	$54	$66
2001	0	2	$286	$20	$24
2002	1	2	$786	$54	$64
2003	0	2	$286	$20	$23
2004	2	2	$1,286	$88	$99
2005	1	2	$786	$54	$59
2006	0	2	$286	$20	$21
2007	0	2	$286	$20	$20
2008	0	2	$286	$20	$20
Undiscounted Total	7	18	$6,071	$417	$480
PV[a] at 7%					**$81**

Source: Author estimates based on interviews with Sugama, Brothers, Bour, and Hernandez in 2009 and an estimated before-tax profit margin of 6.87% based on IRS tax data for the Mining Support Services Industry (NAICS 2131110). See Table 8-1.

[a] PV base year is 1976.

Despite the dramatic improvements in heat tolerance and corrosion resistance, well construction managers have been reluctant to invest in ThermaLock due to higher upfront costs compared to conventional Portland cements. To date, ThermaLock remains a niche product, used in fewer than 30 well cementing jobs since its commercialization a decade ago.

Industry experts interviewed for this analysis cited the incentive structure of well construction project managers as a primary obstacle to increased adoption of ThermaLock. Mangers are rewarded for delivering newly completed wells under budget. The existing incentive structure rewards tangible short-term cost savings, while failing to consider the implications to overall life-cycle well maintenance costs over the well's productive life. Despite this obstacle, experts predict an increase in the rate of adoption over the next five years.

Since commercialization in 1999, ThermaLock has been used in approximately 25 wells, a figure which includes 7 international wells and 18 domestic wells. Geothermal production wells account for 5 international and 9 domestic wells in Table 8-3. The balance of international and domestic wells represent steam or gas injection wells associated with enhanced oil recovery projects.

8.4.2 Economic Benefits to End Users

DOE-developed cement technology embodied in the commercialized product ThermaLock has provided estimated benefits with PV of $15.7 million discounted at 7% to domestic well operators in the geothermal and oil industries. This estimate of benefits to end users was obtained using a well life-cycle cost comparison approach using well construction costs and expected annual maintenance costs for a prototypical well cemented with ThermaLock in place of traditional Portland-based well cement. Table 8-4 presents the benefits estimate for each well type.

Table 8-4. Total Benefits to End Users of High-Temperature Cement, 1999–2008

Well Type	Average Annual Avoided Cost Per Well (thousands $2008)	Well Count	End-User Benefits (thousands $2008)
Geothermal production wells	$1,061	9	$9,549
Enhanced oil recovery injection wells	$684	9	$6,156
Total	**—**	**18**	**$15,705**

Note: Avoided cost per well for a depth of 5,000 feet with industry standard borehole diameters. Cost savings reflect avoided annual well remediation costs and avoided new well construction every 5 years over a 20-year time horizon. Well count based on estimates provided in industry interviews.

Given the fundamental difference in initial costs for geothermal production wells with injection wells, the analysis was conducted for both types of wells. The net cost savings per year are discounted to the point of investment using an industry appropriate discount rate. The resulting average avoided cost per well is then multiplied by the number of wells cemented with ThermaLock in the United States since its commercialization to estimate national benefits. International wells completed with ThermaLock were omitted from this analysis as the benefits associated with these wells are not directly attributed to a U.S. entity.

Average annual avoided costs per well were estimated for a prototypical well by comparing the expected life-cycle costs for a well completed with conventional cement to the costs for the same well completed with ThermaLock over a 20-year time horizon. The resulting average annual avoided costs were $1,061,000 and $684,000 for the prototypical geothermal and enhance oil recovery (EOR) injection well, respectively. Table 8-5 presents the projected life-cycle costs for each well type for the alternative cementing scenarios, as well as other underlying assumptions and inputs used in the analysis.

Table 8-5. Comparison of Lifecycle Costs for a Prototypical Well by Application and Cement Type

Application	Cement Type	
	Portland	**ThermaLock**
Geothermal Production Wells		
Drilling and completion costs[a,b]	$1,750,000	$2,000,000
Annual maintenance costs[c]	$150,000	$0
Useful lifetime[b,c]	5 years	20 years
Enhanced Oil Recovery Injection Wells		
Drilling and completion costs	$500,000	$571,000
Annual maintenance costs	$150,000	$0
Useful lifetime	5 years	20 years

Note: Assumed well depth of 5,000 feet in all cases.
[a] Source: U.S. DOE (2007).
[b] Source: Author interviews with well cementing service industry experts.
[c] Source: U.S. DOE (2005a).

Based on the previous work of Augustine et al. (2006), a cost multiplier of 3.5 was used to adjust the initial drilling and completion costs in geothermal wells compared to EOR injection wells.[1] Annual

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[2] Augustine et al. (2006) found that normalized well costs at geothermal sites were often 2 to 5 times greater than costs for oil and gas wells at comparable depths.

maintenance costs and expected lifetimes were assumed to be similar for both geothermal and EOR injection wells. Costs projected over a 20-year time horizon to estimate each well's total life-cycle costs.

Using the assumptions listed in Table 8-5, time series of expected costs were developed for each type of well under two scenarios. Table 8-6 presents the time series of expected cost savings for 5,000-foot deep geothermal and EOR injection wells cemented using ThermaLock in lieu of Portland cement.

The annual avoided costs per well presented in Table 8-6 were then applied to the number of domestic wells cemented with ThermaLock since its commercialization in 1999 (see Table 8-7). Cementing experts from Halliburton that were interviewed estimated that fewer than 20 wells have been completed using ThermaLock in the United States over the last 10 years. Published case studies and information obtained from interviews were used to develop a timeline of the number of domestic projects completed each year. The sum of annual cost savings from domestic wells is added to the before-tax profits yields the total social benefits for each year.

Table 8-6. Annual Avoided Costs per Well by Well Type (thousands $2008)

Period	**Annual Avoided Costs Per Well**	
	Geothermal	**EOR Injection**
0	–$250	–$71
1	$150	$150
2	$150	$150
3	$150	$150
4	$150	$150
5	$1,750	$500
6	$150	$150
7	$150	$150
8	$150	$150
9	$150	$150
10	$1,750	$500
11	$150	$150
12	$150	$150
13	$150	$150
14	$150	$150
15	$1,750	$500
16	$150	$150
17	$150	$150
18	$150	$150
19	$150	$150
Undiscounted Total	$7,400	$3,829

Table 8-7 summarizes the total social benefits directly attributable to ThermaLock cement.

Table 8-7. Total Benefits of High-Temperature Cement, 1999–2008 (thousands $2008)

Year	Domestic Wells Cost Savings	Before-Tax Profits	Total Benefits
1999	$0	$86	$86
2000	-321	$66	-$255
2001	-21	$24	$3
2002	$279	$64	$343
2003	$579	$23	$602
2004	$879	$99	$978
2005	$3,129	$59	$3,188
2006	$3,429	$21	$3,450
2007	$3,729	$20	$3,749
2008	$4,029	$20	$4,049
Undiscounted Total	$15,711	$480	$16,191
PV[a] at 7%			**$2,097**

Note: In 1999, there were only international sales of ThermaLock. No sales reported in 2009.

[a] Base year is 1976, which is the first year of DOE program expenses.

Corporate before-tax profits account for 3% of total social benefits, while the overwhelming majority of social benefits are derived from cost savings to well operators. The fourth column in Table 8-7 is the PV of the net avoided costs per year from using ThermaLock. Totaling the net avoided costs over the 20-year time horizon yields the average estimated life-time cost savings per well. The next step is determining the share of total benefits that are attributable to research funded by and/or conducted through DOE's GTP.

8.4.3 Environmental Benefits

No environmental benefits are associated with using high-temperature cement. The technology lowers the cost of well maintenance. However, there is no evidence that it has increased the production of geothermal energy.

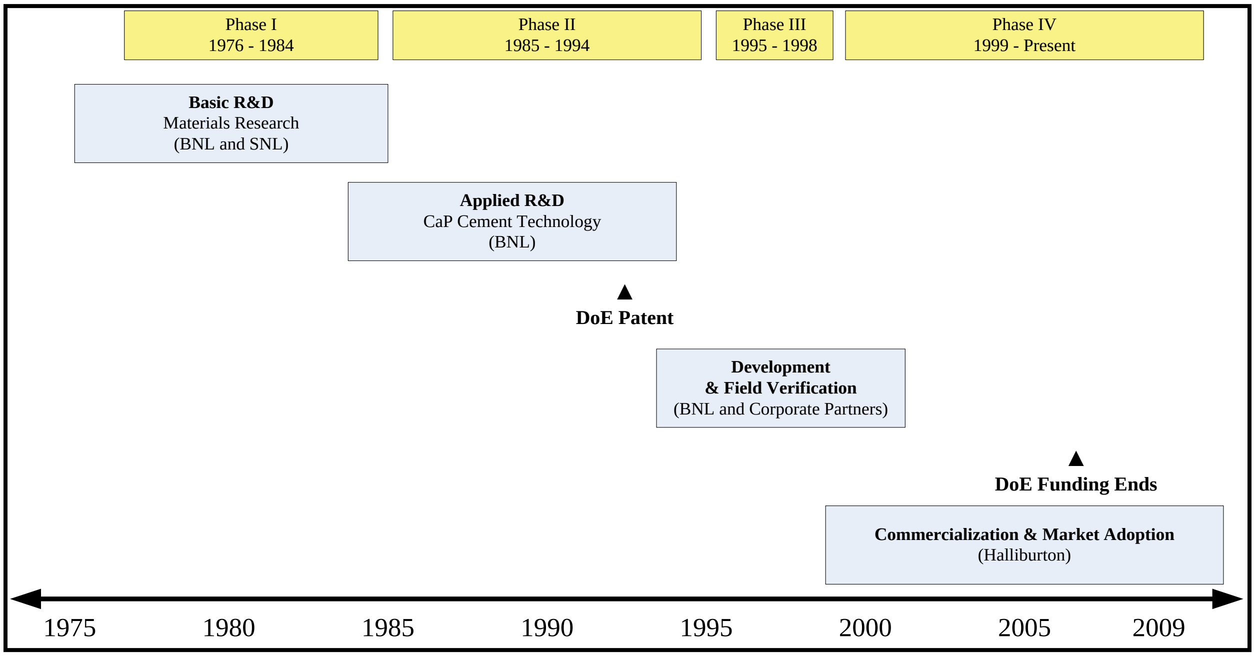
8.4.4 Security Benefits

No security benefits were identified associated with using high-temperature cement.

8.5 Attribution Share

A review of existing publications and internal reports, combined with technical interviews of participating scientists and industry experts, provided information to assess the relative share of the benefits that are attributable to DOE. The development timeline for this technology occurred in three major phases over a 24-year period starting in 1976. Figure 8-1 summarizes the R&D stages and major technology milestones.

Figure 8-1. High-Temperature Cement Technology Development Timeline, 1976–2006



▲The U.S. Patent and Trademark Office awards DOE a patent on CaP cement on September 21, 1993.
▲Halliburton commercializes CaP cement under the trade name ThermaLock, February 1999.

Phase I consisted of basic research conducted at Sandia National Laboratories, Los Alamos National Laboratory, and Oak Ridge National Laboratories over a seven-year period to develop a fundamental understanding of the chemical and physical properties of various cement formulations resulting in a cementious material. Although materials research was underway before the geothermal program was created, 1976 marked the beginning of a more formal effort pursuing improved well cements specifically for geothermal wells.

Phase II consisted of applied research over a 10-year period between 1984 and 1994. Brookhaven National Laboratory, in collaboration with selected industry partners, conducted field tests to identify cementious materials for use in geothermal wells. In 1993, BNL patented the high-temperature cement technology under the title *Phosphate-Bonded Calcium Aluminate Cements* (Sugama, 1993).

Phase III, the final stage of the BNL cement program, began in 1994 and continued until 1999, culminating in the commercialization of the high-temperature cement by Halliburton under the trade name ThermaLock. Phase III primarily consisted of additional field testing in harsh well environments and final commercial product development by BNL’s corporate cost-sharing partners.

Development activities under Phase III were co-funded by DOE’s Office of Geothermal Technologies and three corporate partners: Halliburton, Unocal Corporation, and CalEnergy Operating Corporation. Halliburton was the primary cost-sharing partner and was responsible for conducting technical and economic feasibility studies for the BNL-developed cements and for contributing to the formulation of the final field tested cements. Unocal provided information on compatibility of BNL cements with cementing equipment, operations, and processes currently used in the field. CalEnergy was responsible for field testing BNL-developed cements to validate the cements' integrity and reliability following prolonged exposure in functioning geothermal wells.

Table 8-8 provides a matrix of the sequential elements of the R&D timeline presented in Figure 8-1. During interviews, experts were asked to assessing DOE's contribution to the development of CaP cements was considered at each stage, from preliminary investigations and basic materials research, component and systems development, and validation and testing through to commercialization. Based on these interviews, published literature, and observable technology transfer, DOE's influence at each stage is assigned a corresponding percentage based on the following descriptors and ranges of influence:

- Overwhelming (80–100%)
- Dominant (60–80%)
- Very important (40–60%)
- Influential (20–40%)
- None to minimal (0–20%)

Table 8-8. A Matrix for Assessing DOE Attribution of High-Temperature Cement Technology by Stage

Categories of Information Needed for Additionality Assessment	**Technology Timeline (Stage of Research, Development, and Commercialization)→**						
	Preliminary & Detailed Investigation	**Develop Components**	**Develop System**	**Validate/ Demonstrate**	**Commercialize**	**Market Adoption**	**DOE Attribution**
What DOE did – Funds – Activities (e.g., R&D, catalyze) – Outputs	▪ GTP initiated to assist in removing barriers to expanded development of geothermal resources	▪ Conducted basic research on cement chemistry and physical properties	▪ Laboratory evaluation of cement performance including compression, tensile strength, and corrosion resistance	▪ Provided cost sharing opportunity to conduct field demonstration. ▪ Patented initial CaP cement formulation.			48% of benefits attributed to DOE
What others did (Rival explanations)		▪ ANL developed parallel ceramic based cement with Schlumberger, commercialized as CemCrete	▪ HAL made CaP cement usable in the field by improving pumpability and setup time	▪ Unocal provided Indonesian geothermal wells for field testing.	▪ HAL commercializes CaP cement under trade name ThermaLock	▪ HAL actively markets ThermaLock for apps in geothermal, EOR.	
Driving/restraining policies/government forces **(Rival explanations)** – Requirements influencing investments in subject technologies	▪ Historical evidence of high cost in geothermal well completions limiting expansion energy production from geothermal resources		▪ DOE effort to reduce drilling costs by 25%				
Description of DOE influence	▪ **Dominant (70%)** ▪ Early understanding of the importance of specialized cement technology required for geothermal wells	▪ **Overwhelming (90%)** ▪ Determined the trajectory of cement chemistry	▪ **Dominant (70%)** ▪ Coordinated with HAL to improve initial formulation	▪ **Very Important (50%)** ▪ Provided cost sharing for field testing and laboratory support for evaluation	▪ **Minimal (10%)**	▪ **None (0%)**	
Basis of evidence for influence	▪ DOE reports ▪ Interviews with partners	▪ DOE reports ▪ Interviews with partners	▪ DOE reports ▪ Interviews with partners	▪ DOE reports ▪ Interviews with partners	▪ Interviews with partners	▪ Interviews with partners	
The DOE effect	▪ Accelerated technology entry ▪ Improved performance	▪ Accelerated technology entry ▪ Improved performance	▪ Accelerated technology entry ▪ Improved performance	▪ Accelerated technology entry ▪ Improved performance ▪ Reduced O&M costs			

Notes: BNL – Brookhaven National Lab; ANL – Argonne National Lab; HAL – Halliburton; O&M – Operation and Maintenance

The preliminary and detailed investigation stage relates to targeted materials research conducted by DOE over the first 10 years of the technology timeline. DOE had a dominant influence (70%) in the earliest stage of research to identify and characterize materials to use in cements specially designed for geothermal wells.

DOE had an overwhelming influence (90%) on determining the direction of cement research, choosing to pursue a ceramic-based cement formulation over a more conventional Portland-based design. Also during this period, efforts by researchers at Argonne National Laboratories (ANL) successfully developed a ceramic-based concrete known as Ceramicrete, which is viewed as a limited competing technology, as it is designed for use in extremely low temperature environments (U.S. DOE, 2003). Although ANL cement can be used in oil and gas wells, it was not characterized for use in higher temperature geothermal wells. Therefore, this study does not consider this a rival technology that can directly compete with the geothermal cement technology.

BNL research had a dominant influence (70%) on the final chemical formulations of the CaP cement for which they obtained a patent in 1993. However, the final stages of the systems development stage were facilitated by Halliburton chemists in residence at BNL. Over this time, BNL contributed materials and laboratory space for Halliburton R&D staff that altered the original patented CaP cement formulation to overcome performance characteristics related to the application of the cement at well sites. Halliburton's contributions improved the cement's pumpability and extended the setup time by adding chemical retardants to the BNL formulation.

Brookhaven National Laboratories continued to have a very important influence (50%) on the technology during the validation and testing stages by providing analytical testing equipment and laboratory space to conduct environmental exposure tests in parallel with field testing in Indonesian geothermal wells. Following initial field testing, BNL continued to pursue research aimed at lowering the costs of CaP cements by substituting some inputs with lower cost materials, such as fly ash and slag material, to lower the production price. This DOE-funded research continued through 2008.

Since commercialization in 1999, Halliburton has marketed ThermaLock for use in domestic and international geothermal and EOR injection wells. DOE has had no direct involvement (0% influence) in the market adoption of ThermaLock. Although the market adoption of ThermaLock has been slow due to a higher initial cost compared with conventional cements, the adoption rate is expected to increase in the near future. Availability of long-term well performance data at existing ThermaLock cemented wells will further reduce investment risk and uncertainty, allowing for increased adoption by the geothermal industry and ultimately leading to both an increase in sales and a reduction in operation and maintenance costs in the future.

Averaging the influence factors over each stage in the technology development cycle yields an estimated 48.3%. Table 8-9 reports the total benefits developed in Section 8.3 and the benefits attributable to DOE. Roughly half of the total benefits realized from the development of CaP cement, or approximately $1.0 million (PV at 7%), are directly attributable to the GTP's research and development activities.

Table 8-9. High-Temperature Cement Technology Benefits Attributable to DOE, 1999–2008 (thousands $2008)

Year	Total Benefits	DOE Attributed Benefits[a]
1999	$86	$41
2000	-$255	-$123
2001	$3	$1
2002	$343	$165
2003	$602	$291
2004	$978	$472
2005	$3,188	$1,540
2006	$3,450	$1,666
2007	$3,749	$1,811
2008	$4,049	$1,955
Undiscounted Total	$16,191	$7,820
PV[b] at 7%	**$2,097**	**$1,013**

[a] Based on 48.3% attribution.

[b] Base year is 1976, which is the first year of DOE program expenses.

8.6 Benefit-Cost Analysis

Table 8-10 lists the economic benefits attributed to DOE that were developed in Sections 8.3 and 8.4. The PV of total benefits (adjusted to $2008) equaled $1.0 million discounted at 7% from 1976 to 2008 ($3.2 million discounted at 3%). DOE program expenditures associated with cement materials research are also presented in Table 8-10.

The expenditures in Table 8-10 are built up from program expenses associated with cement materials research and demonstration activities (Sugama, 2010) and represent approximately 0.1% of DOE's total GTP budget over this time period (PV of $9.1 million discounted at 7%). DOE's investment in high-temperature cement technology yielded −$925 million in net benefits discounted at 7% ($162 million discounted at 3%).

Table 8-10. High-Temperature Cement Technology Net Benefits Attributable to DOE, 1976–2008 (thousands $2008)

Year	Total Benefits	DOE Expenditures	Net Benefits
1976	$0	$142	-$142
1977	$0	$142	-$142
1978	$0	$142	-$142
1979	$0	$142	-$142
1980	$0	$142	-$142
1981	$0	$142	-$142
1982	$0	$142	-$142
1983	$0	$142	-$142
1984	$0	$142	-$142
1985	$0	$142	-$142
1986	$0	$142	-$142
1987	$0	$142	-$142
1988	$0	$142	-$142
1989	$0	$142	-$142
1990	$0	$142	-$142
1991	$0	$142	-$142
1992	$0	$142	-$142
1993	$0	$142	-$142
1994	$0	$142	-$142
1995	$0	$142	-$142
1996	$0	$142	-$142
1997	$0	$142	-$142
1998	$0	$142	-$142
1999	$41	$142	-$101
2000	-$123	$142	-$265
2001	$1	$150	-$149
2002	$165	$150	$15
2003	$291	$150	$141
2004	$472	$120	$352
2005	$1,540	$130	$1,410
2006	$1,666	$150	$1,516
2007	$1,811	$142	$1,669
2008	$1,955	$142	$1,813
Undiscounted Total	$7,820	$4,684	$3,136
PV[a] at 7%	**$1,013**	**$1,938**	**-$925**
PV[a] at 3%	**$3,199**	**$3,037**	**$162**

[a] PV base year is 1976.

Table 8-11 summarizes the results of the benefit-cost analysis. In addition to net benefits with PV of $925 million discounted at 7%, the ratio of DOE-attributed benefits to total program expenditures was calculated (referred to as the BCR). The BCR (discounted at 7%) equaled 0.5 (1.1 discounted at 3%). The BCR deceases at higher discount rates, reflecting the timing of expenditures and benefits.

Table 8-11. Benefit-Cost Analysis Results

	Net Benefits (thousands $2008)	**Benefit-Cost Ratio (thousands $2008)**	**Internal Rate of Return**
PV[a] at 7%	-$925	0.5	NA
PV[a] at 3%	$162	1.1	

[a] PV base year is 1976.

IRR serves as a measure of an investment's return by comparing initial investments with discounted cash flows. The IRR for the cement program is undefined because the net benefits are negative.

These results suggest a negative return on DOE's investment, in part because the technology is still in its infancy. Allowing more time for industry to adopt the existing CaP cement technology in geothermal wells would significantly increase the total economic benefits realized and alter the results of this analysis. Depending on the rate of adoption, economic benefits may potentially exceed the total development costs, yielding a positive return on DOE's investment in the near term.

9. KNOWLEDGE BENEFITS[1]

9.1 Introduction

This chapter presents an overview of knowledge output creation and dissemination from R&D supported by DOE's GTP. It also points out specific ties uncovered between the knowledge base and the technologies treated in the detailed benefit-cost analysis presented elsewhere in this report. It is derived from a larger source report (also by Ruegg and Thomas [2010]) that employed bibliometrics, document and database review, and interview in a historical tracing framework to explore linkages between GTP's knowledge outputs from 1976 through 2008, and downstream developments in geothermal power production.

Knowledge outputs resulting from the GTP include patents, papers, presentations, models and codes, resource maps, prototypes, technology demonstrations, test data, research tools, and trained and experienced people. Patents and publications are featured in this brief treatment. Patent and publication citation analyses offer the advantages of providing objectively derived measures to trace knowledge dissemination from government research to other organizations and to innovations close to market. Appendix E provides background on the methodology and construction of data sets used in the analysis; the focus here is on findings.

Principal conclusions, in summary, are that the knowledge base resulting from GTP's expenditures has provided a foundation for further innovation in the geothermal energy industry and also in the gas and oil industries. Multiple technologies important to recent advances in producing power from geothermal resources and in increasing efficiency in gas and oil extraction trace back strongly to GTP-funded research. Specific findings in support of these conclusions include the following:

- From 1976 through 2008, DOE funded a number of organizations to develop a variety of geothermal technologies, resulting in knowledge captured in approximately 90 DOE-attributed patents families (i.e., groups of patents based on the same invention) and more than 3,000 publications, in addition to the resulting prototypes and process advances.
- Of a total population of more than 1,000 geothermal patent families assigned to numerous organizations, 21% were found linked to earlier DOE-attributed geothermal patents and publications. This percentage is second only to that of Chevron, which is billed as the world's largest producer of geothermal energy. Furthermore, greater than 40% of Chevron's own patents were found to have built extensively on earlier DOE-attributed geothermal patents and papers. Among the notable DOE-attributed patent families and publications are those describing Organic Rankine and Kalina thermodynamic cycles, the generation of geothermal energy from hot dry rocks, techniques for treating geothermal brine, advanced drill bits, downhole electronics and data

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[1] This Chapter, prepared by Rosalie Ruegg, TIA Consulting, Inc., and Patrick Thomas, 1790 Analytics, LLC, is based on a larger impact evaluation report coauthored by Ruegg and Thomas, entitled *Linkages from DOE's Geothermal Program R&D to Commercial Power Generation.* (Ruegg and Thomas, 2010). For more details about the approach and findings, consult Appendix E and the larger source report by Ruegg and Thomas.

transmission, improved cements to withstand conditions in wells, and other innovations describing geothermal power plants and power generation.

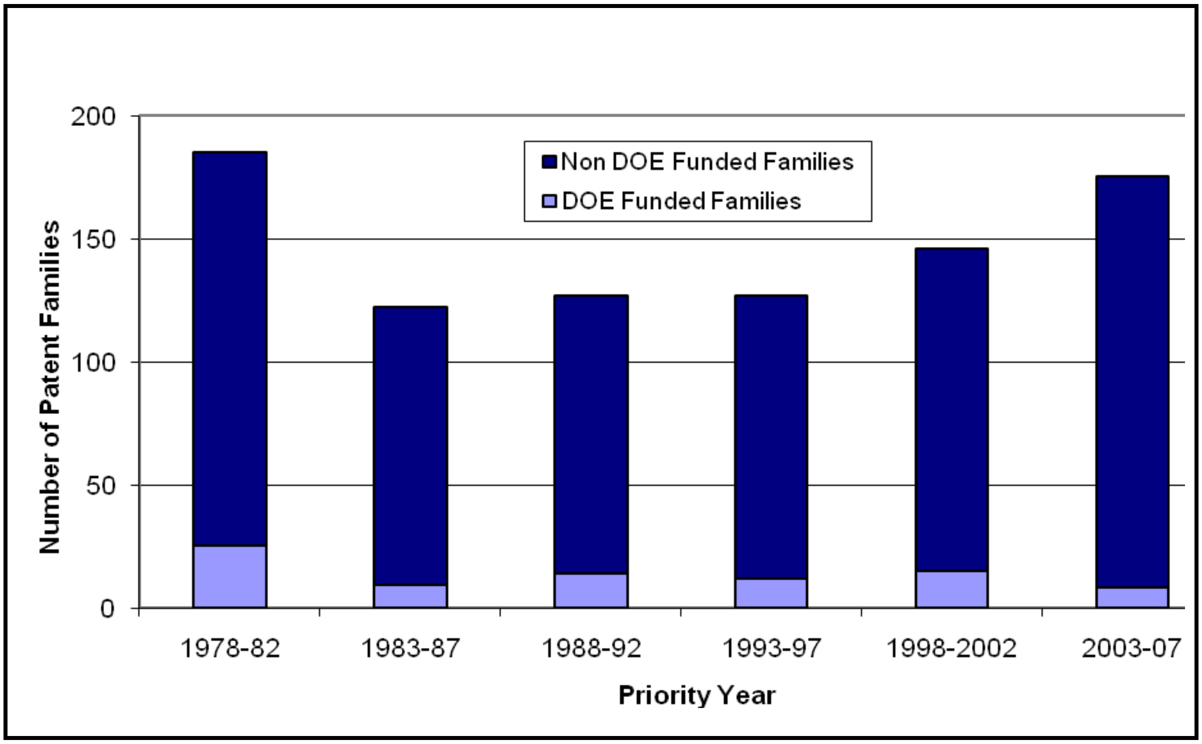
- In addition to the knowledge base captured in patents, papers, and other tacit forms, DOE-funding of geothermal research has trained many technologists and researchers.

9.2 Trends in Geothermal Patents Attributed to DOE and to Others

The study identified 90 geothermal patent families attributable to DOE-funded geothermal R&D. These 90 patent families are constructed from a total of 115 U.S. patents, 16 European Patent Office (EPO) patents, and 17 World Intellectual Property (WIPO) patents. Grouping all the patents that result from the same original patent application into a family avoids multiple counting of what is essentially the same invention.

Figure 9-1 shows the trend of geothermal patenting attributable to DOE in comparison with the wider trend in geothermal patenting from 1978 through 2007, in 5-year increments. To provide the wider trend, the study conducted a patent search that identified a total of 1,016 patent families describing geothermal technologies (made up of a total of 871 U.S. patents, 180 EPO patents, and 234 WIPO patents). The figure reveals that DOE-attributed patent filings in geothermal technology peaked between 1978 and 1982, and fell to a low between 2003 and 2007. The figure also shows that DOE-attributed patents in geothermal comprised a relatively modest share of total geothermal patenting. Yet, this small share has provided a foundation for a large number of further advancements.

Figure 9-1. Comparison of DOE-Attributed Geothermal Patent Families with Those Attributed to Others, Grouped in 5-Year Intervals by Priority-Year, 1978–2007

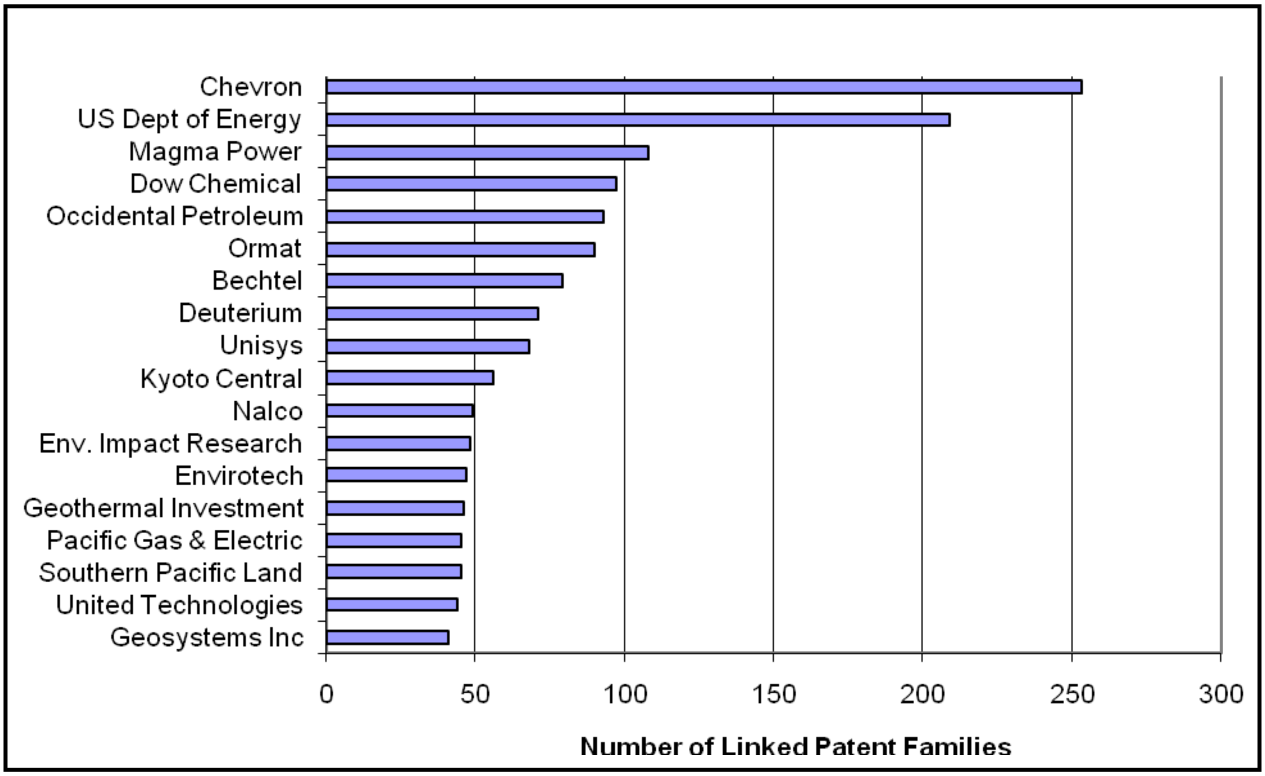


9.3 The DOE-Attributed Knowledge Base in Patents Has Provided a Foundation for Subsequent Innovation in Geothermal Technology

To determine the extent to which the 90 DOE-attributed patents have provided a foundation for further innovation in geothermal technologies, the study analyzed and compared linkages of all of 1,016 geothermal patent families back to earlier geothermal patent families attributed to DOE and to earlier geothermal patent families attributed to other organizations.

Figure 9-2 lists in declining order the organizations whose earlier geothermal patents were linked to the largest number of the 1,016 total geothermal patents that came later. At the head of the figure are Chevron and DOE, with 24.9% of the 1,016 geothermal patent families linked through patent citations to Chevron’s earlier geothermal patents, and 20.6% linked to earlier DOE-attributed geothermal patent families. The results in Figure 9-2 indicate the comparative importance of the patent families attributed to DOE and those assigned to Chevron in the subsequent development of geothermal technology.

Figure 9-2. Organizations Whose Earlier Geothermal Patent Families are Linked to the Largest Number of Later Geothermal Patent Families



Chevron's position is not surprising given that it currently claims to be largest producer of geothermal energy in the world. Much of Chevron's technology in geothermal appears to result from its 2005 merger with Union Oil Company of California (Unocal). Of the 83 Chevron geothermal energy patent families, 80 were originally assigned to Unocal. These Unocal patent families describe a wide variety of technologies related to geothermal energy, including drilling techniques, well casings, and methods for processing geothermal brine and steam.

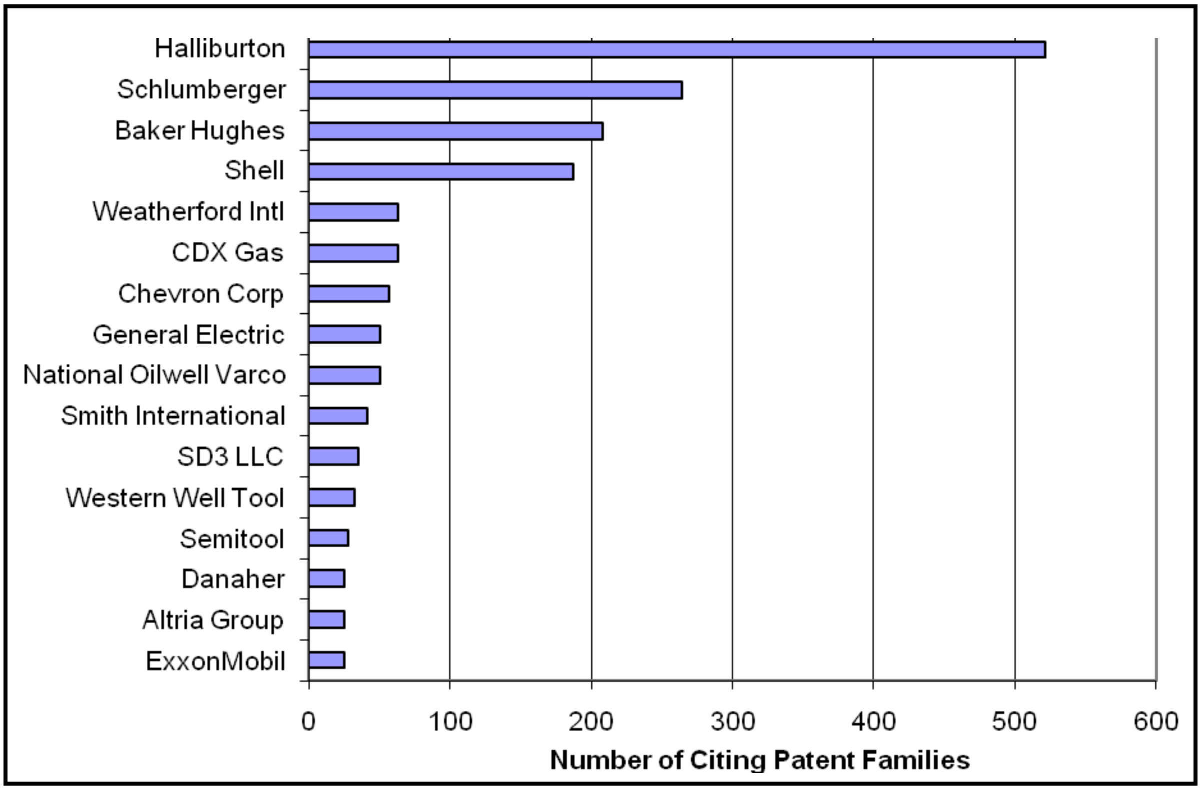
To better appreciate the influence of the DOE-attributed geothermal patent set, it should also be noted that Chevron's portfolio of geothermal patents has itself built extensively on earlier DOE-attributed geothermal patents and papers. In fact, Chevron, together with Ormat, a leading geothermal energy company, are the two organizations with the largest number (as well as the largest percentages) of their geothermal patents linked back to DOE-attributed geothermal patents. Over half of Ormat's geothermal patents families, and over 40% of Chevron's, are linked to earlier DOE-attributed geothermal patent families. Both companies have a series of patent families that build on multiple DOE-attributed patent families. The Chevron patent families that build on the earlier DOE set are focused mainly on methods for treating geothermal brine in order to modify its pH and to control salt precipitation and scale deposition. Ormat's patent families that build on the earlier DOE set describe geothermal power plants and the use of geothermal energy to produce an uninterruptible power supply. These different technologies suggest that the influence of DOE geothermal R&D has been relatively broad.

9.4 DOE-Attributed Geothermal Patent Families Have Influenced Developments Beyond Geothermal, Particularly in the Oil and Gas Industries

The results of tracing forward from the DOE-attributed 90 geothermal patent families to all future patent families as classified by the International Patent Classifications (IPC) show a prominence of linkages of the DOE-attributed patents to later patents in the “Earth & Rock Drilling” IPC class. The second most linkages occur in the IPC category “Geophysics,” which includes seismic testing and exploration. Other IPC areas linked to DOE-funded geothermal research are water and sewage treatment, cements, sprayers and nozzles, and remediation.

Organizations with the largest number of their patents (in all topic areas – not just geothermal) linked through patent citations to earlier DOE-attributed geothermal energy patents are listed in Figure 9-3. The main point to note is the dominance of oilfield services corporations when the industry field is broadened. The three largest of these companies – Halliburton, Schlumberger, and Baker Hughes – have the most patents linked back to the DOE-attributed geothermal energy patents.

Figure 9-3. Organizations with the Largest Number of Patent Families in All Topic Areas Linked to Earlier DOE-Attributed Geothermal Energy Patent Families



Patent families describing lightweight cements for use in wells, including geothermal wells, stem from research by a DOE research team headed by Toshifumi Sugama at Brookhaven National Laboratory, and the related cement technology is featured in the benefit-cost analysis (see Chapter 8). These patent families are linked extensively to subsequent Halliburton patent families describing elements of its

ThermaLock cements. These cements are designed for use in wells operating in harsh environmental conditions, such as geothermal wells and subsea oil and gas wells. All three leading oilfield services companies also have extensive patent portfolios related to drilling techniques and downhole data transmission, and these patent portfolios have large numbers of links to earlier geothermal patent families attributed to DOE in these same areas.

9.5 Individual DOE-Attributed Geothermal Patents with Strong Influence

Some of the DOE-attributed geothermal patents stand out as being particularly notable – some because they are cited by a large number of subsequent geothermal patent families, some because they are highly cited by patents in fields outside the geothermal industry, and others because they are linked to high-impact patents assigned to others.

Table 9-1 shows the DOE-attributed geothermal energy patents linked to the largest number of later geothermal energy patents, implying that these DOE-attributed patents have had a particularly extensive influence on subsequent research in geothermal energy.

Table 9-1. DOE-Attributed Geothermal Patent Families Linked to Largest Number of Later Geothermal Patent Families

Anchor Patent	Issue Date	# Linked Patent Families	Assignee	Title
3640336	1972	58	DOE	Recovery of geothermal energy by means of underground nuclear detonations
3786858	1974	42	DOE	Method of extracting heat from dry geothermal reservoirs
4489563	1984	32	Exergy Inc.	Generation of energy
4196183	1980	24	DOE	Process for purifying geothermal steam
4328106	1982	21	DOE	Method for inhibiting silica precipitation and scaling in geothermal flow systems
4342197	1982	12	Unisys Corp.	Geothermal pump downhole energy regeneration system
3938334	1976	10	Unisys Corp.	Geothermal energy control system and method
5685362	1997	10	University of California	Storage capacity in hot dry rock reservoirs
4380903	1983	8	Unisys Corp.	Enthalpy restoration in geothermal energy processing system
4358930	1982	8	DOE	Method of optimizing performance of Rankine cycle power plants
4167099	1979	6	Occidental Petroleum	Countercurrent direct contact heat exchange process and system
4556109	1985	5	Dow Chemical Co.	Process for cementing geothermal wells
6251179	2001	5	DOE	Thermally conductive cementitious grout for geothermal heat pump systems
4078904	1978	5	DOE	Process for forming hydrogen and other fuels utilizing magma

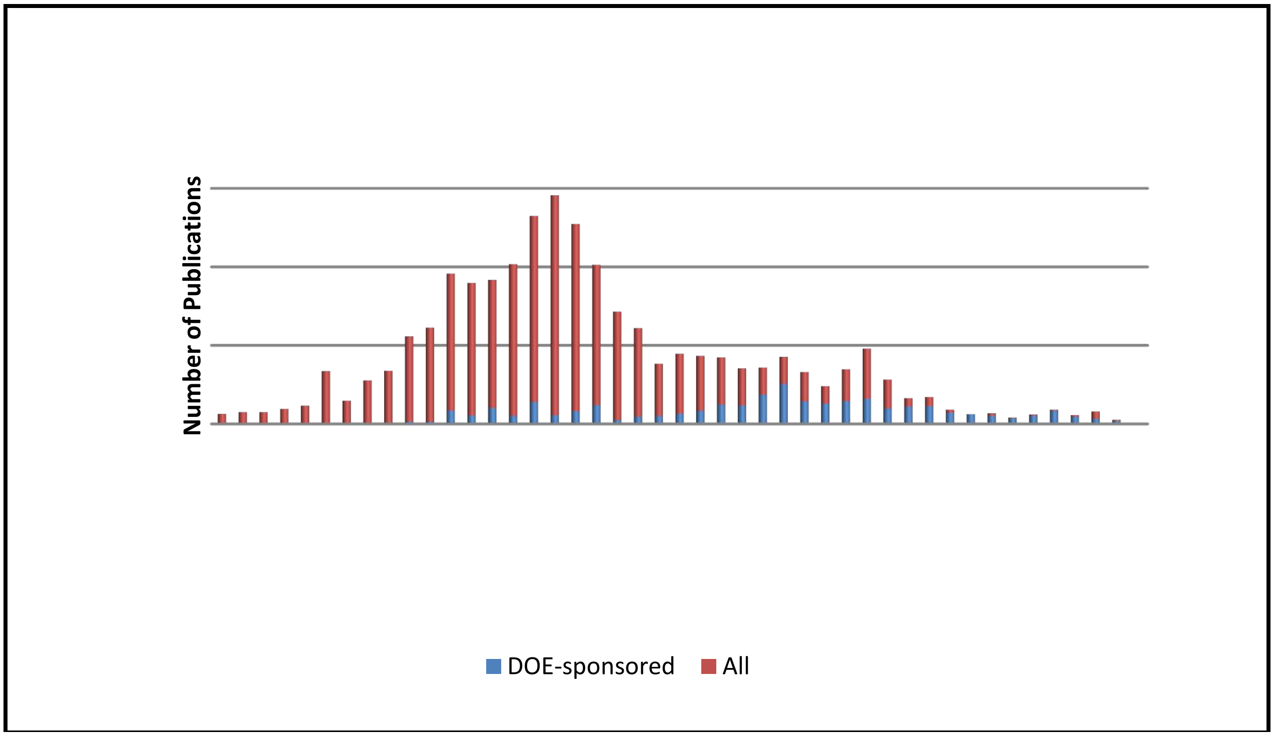
Most of the patents in this figure are relatively old and have long since expired. For example, the two at the head of Table 9-1 – U.S. #3,640,336 and U.S. #3,786,858 – both date from the first half of the 1970s. These patents describe methods for generating geothermal energy from unpromising sites; the former via underground detonations, and the latter through injection of fluid into dry reservoirs. These patents are linked to many later patents describing methods for generating geothermal energy from unpromising locations. One such linked patent that is also listed in Table 9-1 is U.S. #5,685,362. This patent was issued in 1997 and describes methods for generating geothermal energy from hot dry rocks. These are geological strata that exist at high temperatures but do not act like geysers or hot springs because no ground water percolates into them. Geothermal energy is extracted from hot dry rocks by pumping liquid into a well drilled into them, where the liquid is then heated by the rocks. The '362 patent describes such a system and is linked to numerous subsequent geothermal patent families, including families assigned to Ormat.

Another patent in Table 9-1 of particular interest is U.S. #4,489,563. This 1984 patent describes the basic elements of the Kalina thermodynamic cycle for power generation, which is named after Alexander Kalina, the inventor of this patent, whose research was funded by DOE. The Kalina cycle is often used in heat exchangers in geothermal power plants. The '563 patent is linked to 32 subsequent geothermal patents (in addition to 81 other patents). The later patents describe the use of Kalina cycles for low temperature geothermal systems. It is also relevant to examine highly cited patent families of other organizations that are linked back to earlier DOE-attributed geothermal patent families. Among the highly cited geothermal patent assigned to geothermal companies and connected back to the earlier DOE set, a focus was found on the treatment of geothermal brine and the reduction of contaminants in geothermal fluids. Looking more broadly at all industries, the most highly cited patents that link back to earlier DOE-attributed geothermal patent families include Halliburton patents describing lightweight well cements. These patents link back to research at DOE's Brookhaven National Laboratory headed by Sugama, as mentioned earlier. Others include patents describing power and data transmission in downhole applications assigned to Novatek Engineering and National Oilwell Varco (whose patents were originally assigned to Intelliserv, which was acquired in turn by Grant Prideco and by National Oilwell Varco).

9.6 Trends in Geothermal Publications Attributed to DOE and to Others

Figure 9-4 shows the total output of DOE publications in geothermal by year, in comparison with "all" geothermal publications, including DOE publications and those of other organizations. The number of publications from all sources (totaling 18,858) dwarfs the number from DOE (totaling 3,038).

Figure 9-4. DOE Geothermal Publications Compared with All Geothermal Publications, 1965–2009



Source: DOE Office of Scientific & Technical Information (OSTI), geothermal publication database.

Furthermore, during the 65 years prior to the period shown in the figure there had been at least another 500 to 600 papers in geothermal produced by others. Figure 9-4 also shows that the output of geothermal publications from all sources peaked in the early 1980s, while the number attributed to DOE did not peak until the early 1990s. Furthermore, the share of the total comprised by DOE increased over time from 4% of the total in 1981, to 93% of the total by 2005. DOE's funding of geothermal research produced knowledge during a time when other sources appear to have diminished. Evidence presented below suggests that DOE's knowledge base in publications has also supported the development of new enabling advancements in geothermal and other industries.

9.7 Characterization of DOE-Funded Geothermal Publications by Research Organization and by Type

Stanford University's Geothermal Program, which receives funding from DOE through Lawrence Berkeley National Laboratory, led in the number of identified DOE-funded geothermal publications, followed by Idaho National Laboratory, one of several key laboratories carrying out DOE's Geothermal Program, and then by NREL.

Technical reports (50%) and conference papers (44%) were the principal modes of these publications. The rest were journal articles, books, thesis/dissertations, and miscellaneous. This distribution differs from the body of non-DOE sponsored geothermal publications, which had a larger proportion of journal articles and books, and a smaller proportion of technical reports and conference papers.

9.8 Authorship and Citing of Samples of DOE-Funded Geothermal Publications

For each set of publications from the three leading producers of DOE-funded geothermal publications – Stanford, INL, and NREL – authorship and citations were analyzed. For the larger populations of Stanford and INL publications, the analyses were based on random samples. For the smaller population of NREL publications, the analysis was based on the whole population of geothermal publications found in the OSTI database.[2]

9.8.1 Stanford Geothermal Publications Funded by DOE

The distribution of the sample of Stanford papers by topic showed a clear topical focus, with approximately 50% on reservoirs or wells and 35% on exploration. Most of the publications were conference papers. A strong international component was found in the authoring of these Stanford publications, which may have helped connect U.S. geothermal researchers to knowledge developments in other parts of the world and may also signal global interest in Stanford's research. Most of the authors of the conference papers were affiliated with companies, foreign universities, and institutes and ministries of foreign governments. Other authors were from domestic universities, and U.S. federal, state, and regional government organizations. About half the sample of Stanford publications had received one to five citations, and several had received more. Those citing the publications were heavily affiliated with universities, foreign government organizations, and companies, including Calpine Corporation and Unocal Geothermal, as well as major petroleum companies.

9.8.2 INL Geothermal Publications

Most of the INL publications were technical reports. The major topical focus was reservoirs or wells (34%), followed by exploration (26%), and plant and drilling (8% and 7%, respectively). Other publications pertained to "economic/efficiency and financial studies" (5%) and "information about geothermal "(4%), while 16% were categorized as "other." Most of these publications are authored by universities (52%) and companies (13%) under contract with INL. Other organizations, such as other federal, state, and regional government organizations and associations authored 11%. The participation of many universities across the nation suggests that INL funding of university geothermal research is building expertise in this field across the nation. The presence of companies suggests a commercial interest in sponsored INL research. The presence of state and regional bodies provides an element typically involved in large geothermal projects for power generation, and the participation of associations

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[2] Of 678 publications identified as Stanford University geothermal publications, a random sample of 62 was drawn, sufficient for a confidence level of 90% with an interval of +/- 10. Of 287 papers identified as INL geothermal publications, a random sample of 162 was drawn, sufficient for a confidence level of 95% and an interval of +/- 5. Of 58 publications identified as NREL geothermal publications, one duplicate was eliminated, and the entire population of 57 was used in the analyses.

is an indicator of connections of INL into key dissemination paths. Although a small percentage of these publications had received multiple citations, citing of most of the publications was not strong.

9.8.3 NREL Geothermal Publications

Brochures and booklets comprised the largest share (42%) of NREL publications, followed by technical reports (33%) and conference publications (25%). Reflective of a different role for NREL than Stanford or INL, the predominant topic was informational (61%), followed by economic, efficiency, and financial studies (18%). However, there were also publications in the major technical categories of plant (7%), reservoirs or wells (7%), drilling (2%), and exploration (2%). Almost all the NREL geothermal publications are authored in house by one or more NREL authors, indicating that collaboration with other organizations on these reports was not a major mode of knowledge dissemination. A few of these reports were highly cited**,** but many had not been cited yet. Most active among those citing the NREL geothermal publications were researchers in universities. The other affiliations of those citing included companies, research institutes, interest groups, and other DOE laboratories, namely BNL, INL, and ORNL.

9.9 DOE Geothermal Publications Cited by Geothermal Patents

The previous patent analysis found that at least 45 DOE geothermal publications were cited by geothermal patents. A dozen of these publications were cited heavily – between 30 and 200 times by patents. This finding signals the importance of these publications to technology development and indicates that DOE publications can also provide a major, direct route of knowledge dissemination to downstream innovators. This is not surprising given that DOE laboratory researchers typically publish in the open literature the results of their in-house R&D and do not always patent the results.

The most prominent of the DOE geothermal publications cited by patents are those based on BNL's research in lightweight cement, a featured technology in the benefit-cost analysis. These publications were authored by the Brookhaven group headed by Toshifumi Sugama, identified earlier.

A second area of technology for which later company patents heavily cite earlier DOE geothermal publications concerns data for the performance of PDC drill bits – another technology featured in the benefit-cost analysis. DOE researchers at SNL carried out extensive field tests of PDC drill bit performance and potential application. These publications are linked through citations to large numbers of drilling patents assigned to leading oilfield services companies, notably Halliburton, Schlumberger, Baker Hughes, and Smith International.

Other technologies for which later company patents extensively cite earlier DOE geothermal publications include data communications through drill strings and direct-contact condensers for use in geothermal power plants. The first pertains to publication of the results of SNL's research on the acoustical properties of drill strings and propagation of sound waves in drill string. These publications were heavily cited by subsequent company patents on innovations to increase knowledge of conditions within the drill hole. The second pertains to NREL's publishing of the results of its research on direct-contact condensers which were heavily cited by subsequent company patents on innovations relating to the handling of geothermal fluids in power plants.

9.10 Other Knowledge Outputs

Some important types of DOE knowledge outputs are not well captured by patent and publication analyses. This section provides a brief overview of additional categories of DOE geothermal knowledge outputs.

9.10.1 Computer Models/Codes, Maps of Geothermal Resources, and Test Data

The DOE web site provides links to DOE-supported software programs for modeling geothermal systems and economics, as well as to geothermal resource maps, and databases. Most of these resources can be freely downloaded.[3] In some cases the software must be licensed, but the fees are generally modest. DOE-supported models in geothermal include the TOUGH series of reservoir models. These are used to study fluid processes in geothermal reservoirs, project reservoir capacity, and aid in the planning and management of reservoirs as part of larger systems. Related workshops and symposia held by LBNL have helped disseminate the models and train researchers in their use. (Publications have also helped explain and disseminate the code and are reflected in the publication analysis presented previously.) The TOUGH series of reservoir models is one of the technologies selected for detailed benefit-cost analysis elsewhere in this report, where its use in geothermal projects worldwide, as well as for nuclear storage and CO_2 sequestration, is noted.

INL and others have produced geothermal maps that show subterranean temperatures to provide information about the location and nature of geothermal resources. Again, these maps are freely available, and their creation and dissemination are not adequately captured by the patent and publication analyses.

9.10.2 Human Capital

Trained students and experienced researchers who embody knowledge (human capital) provide another major knowledge benefit not adequately captured by bibliometric analysis. As indicated earlier, universities across the nation have been funded by DOE's GTO. Some of these universities are funded to carry out specific geothermal research projects, such as the New Mexico Technical University, Northern Arizona University, Duke University, Pennsylvania State University, University of North Carolina, University of Utah, and University of California. Beyond this, several other university earth science groups are funded more extensively and some on an ongoing basis. These DOE-supported/university-based geothermal centers include the Energy and Geosciences Institute at the University of Utah; the

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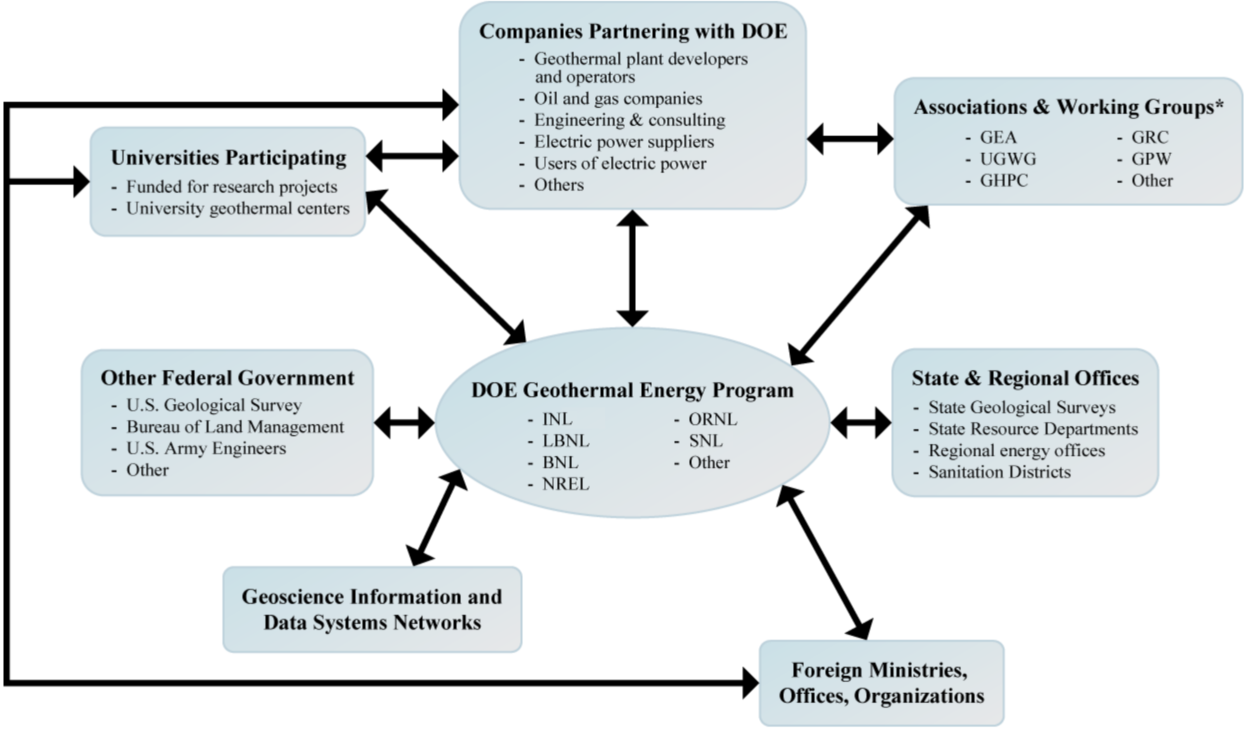
[3] Resources can be found at the following website: www1.eere.energy.gov/geothermal/software_data.html.

Great Basin Center for Geothermal Energy at the University of Nevada, Reno; the Department of Earth Sciences at Southern Methodist University; the Geo-Heat Center at the Oregon Institute of Technology; and Stanford University’s Geothermal Program. Recently, DOE committed funding support to Boise State University over 5 years to lead a consortium of academic institutions and government agencies to establish a National Geothermal Data System (NGDS). Trained geothermal technologists are a result of this funding, in addition to other outputs. The Program also has funded state agencies as way to foster expertise in geothermal energy among those who often play a role in developing geothermal resources within a state. State agencies receiving DOE geothermal funding are primarily located in the West and include agencies in California, Nevada, New Mexico, Utah, Washington, Wyoming, Alaska, Idaho, and Oregon.

The building of a network among geothermal researchers and their organizations also serves to enhance knowledge creation and dissemination. This network, depicted by Figure 9-5, fosters both knowledge creation and flow. A core element of the network is the many partnerships formed by the DOE Geothermal Program over its history. These partnerships link DOE directly to companies that develop new technologies and are positioned to apply the resulting innovations commercially to generate power from geothermal energy. More than 60 companies have entered into cost-sharing partnerships in geothermal research with DOE. Among them are those working principally in geothermal, others known mainly as oil and gas companies, electric power companies, engineering and consulting companies, among others. Participating universities are another core element, as are state and regional offices, associations, other federal agencies, and counterpart organizations abroad.

Figure 9-5. A Network of Organizations Facilitates Geothermal Energy Knowledge Creation and Dissemination



* Notation: GEA, Geothermal Energy Association; UGWG, Utility Geothermal Working Group; GHPC, U.S. Geothermal Heat Pump Consortium; GRC, Geothermal Resource Council; GPW, U.S. Geothermal Heat Pump Consortium.

REFERENCES

Aaheim, H., & Bundschuh, J. (2002). The value of geothermal energy for developing countries. In D. Chandrasekharam and J. Bundschuh, (Eds.), *Geothermal energy resources for developing countries* (pp. 37–52). Lisse, The Netherlands: A.A. Balkema (Swets and Zeitlinger).

Augustine, C., Tester, J., Anderson, A., Petty, S., & Livesay, B. (2006). *A comparison of geothermal with oil and gas well drilling costs.* (Paper SGP-TR-179). Presented at the 2006 Thirty-First Workshop on Geothermal Reservoir Engineering, Stanford University Stanford, CA, January 30 to February 1, 2006.

Bensted, J. (1998). Special cements. In P.C. Hewlett (ed.) *Lea's chemistry of cement and concrete (4th Edition).* Burlington, MA: Butterworth Heinemann.

Berard, B., Hernandez, R., & Nguyen H. (2009). *Foamed calcium aluminate phosphate cement enables drilling and cementation of California geothermal wells*. (SPE 120845) Presented at the 2009 SPE Western Regional Meeting in San Jose, CA, March 24 to 25, 2009.

Blankenship, D., Sandia National Laboratory (2009). Personal communication between Michael Gallaher and Alex Rogozhin, RTI International.

Boudreaux, R., & Massey, K. (1994, March). Turbodrills and innovative PDC bits economically drilled hard formations. *Oil and Gas Journal, 92* (13), 52–5.

Bour, D., AltaRock Energy, Inc. (2009, September 18). Personal communication with Jeffrey Petrusa, RTI International.

Bronicki, L. (2002). Geothermal power stations. In R.A. Meyers (Series Ed.) *Encyclopedia of physical science and technology (Vol. 6.*,3rd ed., pp. 709–18). Academic Press (Elsevier).

Brothers, L. (2006, December 1). CPC resists acid corrosion. *E&P Magazine.* Available at http://www.epmag.com/archives/techWatch/153.htm.

Brothers, L., Halliburton. (2009, August 31). Personal communication with Jeffrey Petrusa, RTI International.

Brugman, J., Hattar, M., Nichols, K., & Esaki, Y. (1994, December). *Next generation power plants*. (EPRI Report 3657-01). Palo Alto, CA: Electric Power Research Institute (EPRI).

Casto, R. (1995, November). Use of bicenter PDC bit reduces drilling cost. *Oil and Gas Journal, 93* (46), 92–6.

DiPippo, R. (2008). *Geothermal power plants: Principles, applications, case studies and environmental impact*. Burlington, MA: Butterworth-Heinemann.

EERE/GEO (Energy Efficiency and Renewable Energy/Geothermal Technologies Program). (2008). *A history of geothermal energy research and development in the United States: Drilling 1976–2006*. Washington, DC: U.S. Department of Energy.

EERE/GTP (Energy Efficiency and Renewable Energy/Geothermal Technologies Program). (2010). *A history of geothermal energy in the united states*. Available at http://www1.eere.energy.gov/geothermal/history.html.

EERE/GTP (Energy Efficiency and Renewable Energy/Geothermal Technologies Program). (2008a, December 31). *A history of geothermal energy research and development: Drilling 1976 to 2006*. Final Lab Draft. Washington DC: U.S. Department of Energy.

EERE/GTP (Energy Efficiency and Renewable Energy/Geothermal Technologies Program). (2008b, December 31). *A history of geothermal energy research and development: Exploration 1976 to 2006*. Final Lab Draft. Washington DC: U.S. Department of Energy.

EERE/GTP (Energy Efficiency and Renewable Energy/Geothermal Technologies Program). (2008c, December 31). *A history of geothermal energy research and development: Reservoir engineering 1976 to 2006*. Final Lab Draft. Washington DC: U.S. Department of Energy.

EERE/GTP (Energy Efficiency and Renewable Energy/Geothermal Technologies Program). (2008d, December 31). *A history of geothermal energy research and development: Energy conversion 1976 to 2006*. Final Lab Draft. Washington DC: U.S. Department of Energy.

Falcone, S., & Bjornstad, D. (2005, December). Leveraging defense research: Social impact of the transfer of polycrystalline diamond drill bit research. *Comparative Technology Transfer and Society, 3*, 267–300. doi: 10.1353/ctt.2006.0004.

Finger, J., & Glowka, D. (1989). *PDC bit research at Sandia National Laboratories*. Sandia Corporation. Washington, DC: Department of Energy. Available at http://www.osti.gov/geothermal/servlets/purl/6107005-GL9XS0/6107005.pdf.

Freedonia Group. (2009). *Drilling products and services to 2012. Drill bit and realer demand by product: Fixed cutter drill bits.* Cleveland, OH: The Freedonia Group, Inc. Available at http://www.freedoniagroup.com/FractionalDetails.aspx?DocumentId=405397.

Gani, R. (1982, November 29). Diamond shear bits pass test in Indonesia's Arun gas field. *Oil and Gas Journal.*

GEA (Geothermal Energy Association). (2009a). *Listing of U.S. geothermal power plants.* Available at http://www.geo-energy.org/information/plants.asp.

GEA (Geothermal Energy Association). (2009b). *Geothermal basics: Notes and references*. Washington, DC: Geothermal Energy Association. Available at http://www.geo-energy.org/aboutGE/notes.asp.

Glitnir (Glitnir Geothermal Research). (2008). *United States geothermal energy market report.* Iceland: Reykjavik.

Glowka, D., & Schafer, D. (1993, September). *Program plan for the development of advanced synthetic-diamond drill bits for hard-rock drilling*. Washington, DC: Department of Energy. doi: 10.2172/10104670.

Glowka, D., Dennis, T., Le, P., Cohen, J., & Chow, J. (1995). *Progress in the advanced synthetic-diamond drill bit program*. Washington, DC: Department of Energy. Available at http://www.osti.gov/bridge/servlets/purl/127986-TvmMq5/webviewable/127986.pdf.

Griliches, Z. (1958). Research costs and social returns: Hybrid corn and related innovations. *Journal of Political Economy, 66.*

Hernandez, R., Halliburton. (2009, October 13). Personal communication with Jeffrey Petrusa, RTI International.

Internal Revenue Service (IRS). (2008). *Statistics of income. Corporation source book.* Washington, DC: Internal Revenue Service. Available at www.irs.gov/pub/irs-soi/04sb1mn213110.xls.

Jones, P. (1988). *Oil: A practical guide to the economics of world petroleum*. Cambridge, UK: Woodhead-Faulkner.

LBNL (Lawrence Berkeley National Laboratory). (2009). *TOUGH workshops and symposia*. Berkeley, CA: LBNL. Available at http://www-esd.lbl.gov/TOUGH2/ TOUGHWORKSHOPS.html.

Leslie, N. P., Zimron, O., Sweetser, R. S., & Stovall, T. K. (2009). Recovered energy generation using an organic Rankine cycle system. *ASHRAE Transactions, 115* (1), 220.

Long, A. (2008). *Improving the economics of geothermal development through an oil and gas industry approach*. Houston, TX: Schlumberger Consulting. Available at http://www.slb.com/media/services/consulting//thermal_dev.pdf.

Madigan, J., & Caldwell, R. (1981). Application for polycrystalline diamond compact bits form analysis of carbide insert and steel tooth bit performance. *Journal of Petroleum Technology, 33*, 1171–9.

Mansfield, E., Rapoport, J., Romeo, A., Wagner, S., & Beardsley, G. (1977). Social and private rates of return from industrial innovations. *Quarterly Journal of Economics, 91*, 221–40.

Masters, G. M. (2004). *Renewable and efficient electric power systems*. Hoboken, NJ: Wiley and Sons.

McDonald, S., & Felderhoff, F. (1996, March). New bits, motors improve economics of slim hole horizontal wells. *Oil and Gas Journal, 94* (11).

Mensa-Wilmot, G. (1997, October). New PDC cutters improve drilling efficiency. *Oil and Gas Journal, 95* (43), 64–70.

Mensa-Wilmot, G. (2003, September 9). *PDC drill bit having cutting structure adapted to improve high speed drilling performance.* U.S. Patent No. 6,615,934. Washington, DC: U.S. Patent and Trademark Office.

O'Sullivan, M., Pruess, K., & Lippmann, M. (2001). State of the art of geothermal reservoir simulation. *Geothermics, 30*, 395–429.

O'Sullivan, M. J. (1980, December). *The DOE code comparison study: Summary of results for problem 4-expanding two-phase system with drainage*. U.S. DOE Contract W-7405-ENG-48. Berkeley, CA: LBNL.

Oldenburg, C., Kneafsey, T., & Rutqvist, J. (2007). Foreword to the special issue containing research results generated using the TOUGH codes. *Energy Conversion and Management, 48*, 1759.

Papadakis, M., & Link, A. (1997). Measuring the unmeasurable: Cost-benefit analysis for new business start-ups and scientific research transfers. *Evaluation and Program Planning, 20* (1), 99–102.

Pruess, K. (1990). *Proceedings of the TOUGH workshop*. Workshop held in Berkeley, CA, September 13–14, 1990. Berkeley, CA: LBNL. Available at http://adsabs.harvard.edu//abs/1990beca.work...13P.

Pruess, K. (1995, March). *Proceedings of the TOUGH workshop*. Lawrence Berkeley Laboratory Report LBL-37200. Berkeley, CA: LBNL. Available at http://www-esd.lbl.gov/TOUGH2//T95.doc.html.

Pruess, K. (1998). *Proceedings of the TOUGH workshop '98*. Lawrence Berkeley Laboratory Report LBL-41995. Berkeley, CA: LBNL.

Pruess, K. (2004). The TOUGH codes—A family of simulation tools for multiphase flow and transport processes in permeable media. *Vadose Zone J., 3,* 738–46.

Pruess, K. (2009). Personal communication between Karsten Pruess and Mike Gallaherheld September 12–14, 2009. Berkeley, CA: LBNL.

Pruess, K. (2009, December). E-mail from Karsten Pruess to Mike Gallaher .

Renner, J. (2009). Personal communication. Mike Gallaher and Alex Rogozhin, RTI International.

REPP (Renewable Energy Policy Project). (2003). *Geothermal energy for electric power: A REPP issue brief*. Washington DC: Renewable Energy Policy Project. Available at http://www.repp.org/repp/index.html.

Ruegg, R., and Jordan, G. (2009). *Guidelines for conducting retrospective benefit-cost studies.* (Internal DOE draft report, not yet released).

Ruegg, R. & Thomas, P. (2010). *Linkages from DOE's geothermal program R&D to commercial power generation.* U.S. Department of Energy, Energy Efficiency and Renewable Energy, publication expected in 2010.

Slack, J.B., & Wood, J. (1982, August 24). Stratapax bits prove economical in Austin chalk. *Oil and Gas Journal, 79,*164–5.

Sugama, T. (1993, September 21). *Phosphate-bonded calcium aluminate cements.* U.S. Patent No. 5,246,496.

Sugama, T. (2006). *Advanced cements for geothermal wells: Final report.* BNL-77901-2007-IR. Upton, NY: Brookhaven National Laboratory.

Sugama, T. U.S. Department of Energy. (2009, July 20). Personal communication with Jeffrey Petrusa, RTI International.

Sugama, T. (2010, February 22). Based on e-mail from Toshifumi Sugama to RTI on February 22, 2010.

Taylor, M. (2007, November). *The state of geothermal technology: Part I: subsurface technology*. Washington, DC: Geothermal Energy Association.

U.S. Bureau of the Census (U.S. Census). (2000). *Historical national population estimates: July 1, 1900 to July 1, 1999*. Washington DC: U.S. Census Bureau, Population Estimates Program, Population Division. Available at http://www.census.gov/popest/archives/1990s/.txt.

U.S. Bureau of the Census (U.S. Census). (2009). *Annual estimates of the resident population for the United States, regions, states, and Puerto Rico: April 1, 2000 to July 1, 2008.* NST-EST2008-01. Washington DC: U.S. Census Bureau. Available at http://www.census.gov/popest/states/NST-ann-est.html.

U.S. DOE (Department of Energy). (1993). *Drilling sideways: A review of horizontal well technology and its domestic application*. DOE/EIA-TR-0565. Washington, DC: Department of Energy, Energy Information Administration. Available at http://tonto.eia.doe.gov/ftproot/petroleum/tr0565.pdf.

U.S. DOE (Department of Energy). (2000a). *Diamond cutter drill bits*. Washington, DC: Department of Energy, Geothermal Energy Program. Available at http://www.nrel.gov/docs/fy00osti/23692.pdf.

U.S. DOE (Department of Energy). (2000b, September). *Geothermal technologies*. Washington DC: U.S. Department of Energy, Geothermal Energy Program.

U.S. DOE (Department of Energy). (2003). *Ceramicrete: Chemically bonded ceramic,* a technology profile. Chicago, IL: Argonne National Laboratory. Available at: http://www.anl.gov/techtransfer/Available_Technologies/Material_Science/Ceramicrete/.

U.S. DOE (Department of Energy). (2005a). *Geothermal today: 2005 Geothermal Technologies Program highlights*. DOE/GO-102005-2189. Golden, CO: National Renewable Energy Laboratory.

U.S. DOE (Department of Energy). (2005b). *Production tax credit for renewable electricity generation. Issues in Focus AEO2005.* Washington, DC: U.S. DOE, Energy Information Administration. Available at http://www.eia.doe.gov/oiaf/aeo/otheranalysis/ aeo_2005analysispapers/prcreg.html.

U.S. DOE (Department of Energy). (2007). *Final report and strategic plan on the feasibility study to asses geothermal potential on Warm Springs Reservation tribal lands.* DE-FG36-05GO15177. Washington, DC: U.S. Department of Energy.

U.S. DOE (Department of Energy). (2008a). *Geothermal Technologies Program, multi-year, development and demonstration plan.* Draft. Washington DC: U.S. Department of Energy.

U.S. DOE (Department of Energy). (2008b). *A history of geothermal energy R&D in the United States: GeoPowering the West.* Draft. Washington, DC: U.S. Department of Energy.

U.S. DOE (Department of Energy). (2009). *Monthly energy review: average retail price of electricity*. Available at tonto.eia.doe.gov/merquery/mer_data. asp?table=T09.09. Accessed on November 19, 2009.

U.S. DOE (Department of Energy). (2010a). *U.S. footage drilled for crude oil developmental wells (thousand feet)* . Available at http://tonto.eia.doe.gov/dnav/pet/hist/ e_ertwo_xwfd_nus_mfa.htm. Accessed on February 19, 2010.

U.S. DOE (Department of Energy). (2010b). *U.S. footage drilled for natural gas exploratory and developmental wells (thousand feet).* Available at http://tonto.eia.doe.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EERTWG_XWF0_NUS_MF&f=A. Accessed on February 19, 2010.

U.S. DOE (Department of Energy). (2010c). *Table 4. Estimated carbon dioxide emissions rate from generating units at U.S. electric plants by Census Division, 1998 and 1999 (pounds per kilowatthour)*. Available at http://www.eia.doe.gov/cneaf/ electricity/page/co2_report/co2report.html#electric. Accessed on February 19, 2010.

U.S. DOE (Department of Energy). (2010d). *Table 8.2a Electricity net generation:1949–2008*. [web page]. Available at http://www.eia.doe.gov/emeu/aer/txt/stb0802a.xls. Accessed on February 19, 2010.

Wampler, C., & Myhre, K. (1990). Methodology for selecting PDC bits cuts drilling costs. *Oil and Gas Journal*, *88* (3), 39–44.

Wise, J. L., Roberts, T., Schen, A., Matthews, O., Pritchard, W., Mensa-Wilmot, G., Ernst, R., Radtke, R., Riedel, R., & Hanaway, J. (2004). Hard-rock drilling performance of advanced drag bits. *Geothermal Resources Council Transactions*, *28*.

APPENDIX A:

GOVERNMENT'S ROLE IN TECHNOLOGY DEVELOPMENT

Underlying the benefits analysis is a conceptual question of what the role of government is in developing and deploying new technologies. The theoretical basis for government's role in market activity is based on the concept of market failure. Market failure is typically attributed to market power, imperfect information, externalities, and public goods. The explicit application of market failure to justify government's role in innovation, and in R&D activity in particular, is a relatively recent phenomenon within public policy.

Market failure, particularly technological or innovation market failure, results from conditions that prevent organizations from fully realizing or appropriating the benefits created by their investments. This happens when conditions prevent the full appropriation of the benefits by the R&D-investing firm from a marketable technology produced through an R&D process. Typically other firms in the market or in related markets will realize some of the profits from the innovation. The R&D-investing firm will then calculate, because of such conditions, that the marginal benefits it can receive from a unit investment in such R&D will be less than could be earned in the absence of the conditions, reducing the appropriated benefits of R&D below their potential, namely the full social benefits. Thus, the R&D-investing firm might underinvest in R&D, relative to what it would have chosen as its investment in the absence of the conditions.

Stated another way, the R&D-investing firm might determine that its private rate of return is less than its private hurdle rate (i.e., the firm's minimum acceptable rate of return); therefore, it will not undertake socially valuable R&D.

A number of non-mutually exclusive factors can explain why a firm will perceive that its expected rate of return will fall below its hurdle rate:

- High technical risk (i.e., the outcomes of its R&D might not be technically sufficient to meet needs) might cause market failure, given that when the firm is successful, the private returns fall short of the social returns.

- High technical risk can relate to high commercial or market risk, as well as to technical risk, when the requisite R&D is highly capital intensive. The investment could require too much capital for a firm—any firm—to feel comfortable with the outlay; thus, the firm will not make the investment, even though it would be better off if it had, and so would society.

- Many R&D projects are characterized by a lengthy time interval until a commercial product reaches the market.

- It is not uncommon for the scope of potential markets to be broader than the scope of the individual firm’s market strategies, so the firm will not perceive economic benefits from all potential market applications of the technology.

- The evolving nature of markets requires investment in combinations of technologies that, if they existed, would reside in different industries that are not integrated. Due to the fact that such conditions often transcend the R&D strategy of individual firms, such investments are not likely to be pursued.

- A situation can exist when the nature of the technology is such that it is difficult to assign intellectual property rights.

- Industry structure can raise the cost of market entry for applications of the technology.

- Situations can exist where the complexity of a technology makes agreement with respect to product performance between buyers and sellers costly.

These factors, individually or in combination, can create barriers to innovation and thus lead to private underinvestment in R&D because of market failure. As a result, there is frequently a role for government to support the development of technologies that have large spillover benefits or are characterized by high risk and high return.

APPENDIX B:

INTERVIEWS

As shown in Table B-1, a total of 22 informal interviews were conducted as part of the study. The interviews were structured discussions and no formal interview guide was used. The majority of the interviews were with private-sector industry experts and academics that participated in the research or led the commercialization of the technologies. The interviews were used primarily to identify how technology development and industry practices would have evolved in the absence of DOE's activities.

Table B-1. Interviews by Technology

Technology	**Number of Interviews**	
	DOE	**Non-DOE**
PDC drill bits	1	1
TOUGH Models	2	7
Binary Cycle	2	4
High-temperature cement	2	4
Total	7	15

Industry and academic experts were selected for interviews based on their knowledge of the technology area and their familiarity with the R&D activities conducted by DOE. Initial contacts were provided by DOE. In all instances RTI asked the initial contacts to recommend additional experts who could comment on the subject area and these "networks" were fully explored. In addition, RTI identified and pursued authors of key papers published in the professional literature.

The fewest number of interviews were conducted for the PDC drill bit technology. For this technology, there is a well-developed base of literature from which to assess the technology development and DOE's role. For example, over 10 published studies document the economic benefits of PDC drill bits. In addition, economic impact studies were conducted in the late 1990s that had used an extensive number of interviews to assess and document DOE's role in the development and commercialization of PDC drill bits. RTI leveraged the information from past studies and past interviews rather than re-contacting the same individuals 10 years later and asking them to recall similar information. Human recollection is a common impediment to conducting retrospective impact studies; hence, earlier studies are likely to have more accurate information regarding DOE's contributions.

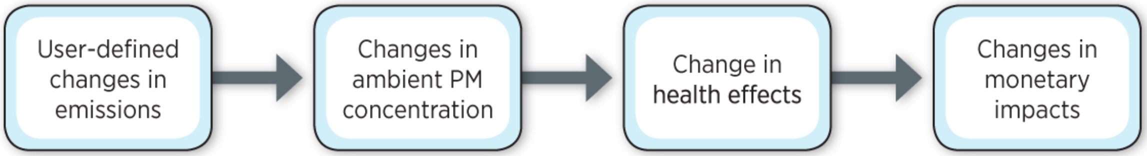
APPENDIX C:

SUMMARY OF THE CO-BENEFITS RISK ASSESSMENT (COBRA) MODEL[1]

The Co-Benefits Risk Assessment (COBRA) model provides estimates of health effect impacts and the economic value of these impacts resulting from emission changes. The COBRA model was developed by the U.S. Environmental Protection Agency (EPA) to be used as a screening tool that enables users to obtain a first-order approximation of benefits due to different air pollution mitigation policies.

At the core of the COBRA model is a source-receptor (S-R) matrix that translates changes in emissions to changes in particulate matter (PM) concentrations. The changes in ambient PM concentrations are then linked to changes in mortality risk and changes in health incidents that lead to health care costs and/or lost workdays. Figure C-1 provides an overview of the modeling steps.

Figure C-1. COBRA Model Overview



Source: EPA (2006)

C.1 Changes in Emission → Changes in Ambient PM Concentrations

The user provides changes (decreases) in emissions of pollutants ($PM_{2.5}$, SO_2, NO_x) and identifies the economic sector from which the emissions are being reduced. These changes are in total tons of pollutants by sector for the U.S. economy for the chosen analysis year. The economic sectors chosen determine the underlying spatial distribution of emissions and hence the characteristics of the human population that is affected.[2] For example, emissions reductions due to the use of geothermal technology are typically applied to coal plants in electric utilities. Reductions due to the use of geothermal technology are applied to coal, oil, and natural gas plants in electric utilities.

The S-R matrix consists of fixed transfer coefficients that reflect the relationship between annual average $PM_{2.5}$ concentration values at a single receptor in each county (a hypothetical monitor located at the county centroid) and the contribution by $PM_{2.5}$ species to this concentration from each emission source. This matrix provides quick but rough estimates of the impact of emission changes on ambient $PM_{2.5}$ levels as compared to the detailed estimates provided by more sophisticated air quality models (U.S. EPA, 2006).

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[1] This Appendix was prepared by Michael Gallaher, RTI International.

[2] The COBRA model has a variety of spatial capabilities. However, for this study there was limited information on the specific location of pollution reductions. Thus, a national analysis was conducted where the national distribution of emissions by fuel type, by sector (e.g., special distribution of national coal emissions in the electricity sector) was used to determine the emission location as input to the S-R matrix.

C.2 Changes in Ambient PM Concentrations → Changes in Health Effects

The model then translates the changes in ambient PM concentration to changes in incidence of human health effects using a range of health impact functions and estimated baseline incidence rates for each health endpoint. The data used to estimate baseline incidence rates, and the health impact functions used vary across the different health endpoints. To be consistent with prior EPA analyses, the health impact functions and the unit economic value used in COBRA are the same as the ones used for the Regulatory Impact Analysis of the Clean Air Interstate Rule (U.S. EPA, 2005).[3]

The model provides (in the form of a table or map) changes in the number of cases for each health effect between the baseline emissions scenario (included in the model) and the analysis scenario. The different health endpoints are included in Table C-1.

Table C-1. Health Endpoints Included in COBRA

Health Effect	Description/Units
Mortality	Number of deaths
Chronic bronchitis	Cases of chronic bronchitis
Nonfatal heart attacks	Number of nonfatal heart attacks
Respiratory hospital admissions	Number of cardiopulmonary-, asthma-, or pneumonia-related hospitalizations
Cardiovascular related hospital admissions	Number of cardiovascular-related hospitalizations
Acute bronchitis	Cases of acute bronchitis
Upper respiratory symptoms	Episodes of upper respiratory symptoms (runny or stuffy nose; wet cough; and burning, aching, or red eyes)
Lower respiratory symptoms	Episodes of lower respiratory symptoms: cough, chest pain, phlegm, or wheeze
Asthma emergency room visits	Number of asthma-related emergency room visits
Minor restricted activity days	Number of minor restricted activity days (days on which activity is reduced but not severely restricted; missing work or being confined to bed is too severe to be MRAD)
Work days lost	Number of work days lost due to illness

Source: COBRA User Manual

Each health effect is described briefly below. For additional detail on the epidemiological studies, functional forms, and coefficients used in COBRA, see Appendices C of the COBRA user's manual (U.S. EPA, 2006) and Abt (2009).

Mortality researchers have linked both short-term and long-term exposures to ambient levels of air pollution to increased risk of premature mortality. COBRA uses mortality risk estimates from an epidemiological study of the American Cancer Society cohort conducted by Pope et al. (2002). COBRA includes different mortality risk estimates for both adults and infants. Because of the high monetary value

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[3] For a detailed discussion of studies used for health impact functions and unit values, see U.S. EPA (2005).

associated with prolonging life, mortality risk reduction is consistently the largest health endpoint valued in the study.

Chronic bronchitis is defined as a persistent wet cough and mucus in the lungs for at least 3 months for several consecutive years, and it affects approximate 5% of the population (Abt, 2009). A study by Abbey et al. (1995) found statistically significant relationships between $PM_{2.5}$ and PM_{10} and chronic bronchitis.

Nonfatal heart attacks were linked by Peters et al. (2001) to PM exposure. Nonfatal heart attacks are modeled separately from hospital admissions because of their lasting impact on long-term health care costs and earning.

Hospital admissions include two major categories: respiratory (such as pneumonia and asthma) and cardiovascular (such as heart failure, ischemic heart disease). Using detailed hospital admission and discharge records, Sheppard et al. (1999) investigated asthma hospital emissions associated with PM, carbon monoxide (CO), and ozone, and Moolgavkar (2000 and 2003) and Ito (2003) found a relationship between hospital admissions and PM. COBRA includes separate risk factors for hospital admissions for people aged 18 to 64 and aged 65 and older.

Acute bronchitis, defined as coughing, chest discomfort, slight fever, and extreme tiredness lasting for a number of days, was found by Dockery et al. (1996) to be related to sulfates, particulate acidity, and, to a lesser extent, PM. COBRA estimates the episodes of acute bronchitis in children aged 8 to 12 from pollution using the findings from Dockery et al.

Upper respiratory symptoms include episodes of upper respiratory symptoms (runny or stuffy nose; wet cough; and burning, aching or red eyes). Pope et al. (2002) found a relationship between PM and the incidence of a range of minor symptoms, including runny or stuffy nose; wet cough, and burning; aching or red eyes.

Lower respiratory symptoms in COBRA are based on Schwarz and Neas (2000) and focus primarily on children’s exposure to pollution. Children were selected for the study based on indoor exposure to PM and other pollutants resulting from parental smoking and gas stoves. Episodes of lower respiratory symptoms are coughing, chest pain, phlegm, or wheezing.

Asthma related emergency room visits are primarily associated with children under the age of 18. Norris et al. (1999) found significant associations between asthma ER visits and PM and CO. To avoid double counting, hospitalization costs (discussed above) do not include the cost of admission to the emergency room.

Minor restricted activity days (MRAD) in COBRA were based on research by Ostro and Rothschild (1989). MRADs include days on which activity is reduced but not severely restricted (e.g., missing work or being confined to bed is too severe to be an MRAD). They estimated the incidence of MRADs for a national sample of the adult working population, aged 18 to 65, in metropolitan areas. Due to the fact that this study is based on a “convenience “sample of nonelderly individuals, the impacts may be underestimated because the elderly are likely to be more susceptible to PM-related MRADs).

Work loss days were estimated by Ostro (1987) to be related to PM levels. Based on an annual national survey of people aged 18 to 65, Ostro found that 2-week average PM levels were significantly linked to work loss days. Yet, the findings showed some variability across years.

C.3 Changes in Health Effects → Changes in Monetary Impacts

COBRA translates the health effects into changes in monetary impacts using estimated unit values of each health endpoint. The per-unit monetary values are described in Appendix F of the COBRA user’s manual (U.S. EPA, 2006). Estimation of the monetary unit values vary by the type of health effect. For example, reductions in the risk of premature mortality are monetized using value of statistical life (VSL) estimates. Other endpoints such as hospital admissions use cost of illness (COI) units that include the hospital costs and lost wages of the individual but do not capture the social (personal) value of pain and suffering.

C.4 Limitations

It should be noted that COBRA does not incorporate effects of many pollutants, such as carbon emissions or mercury. This has two potential implications. First, other pollutants may cause or exacerbate health endpoints that are not included in COBRA. This would imply that reducing incidences of such health points are not captured. Second, pollutants other than those included in COBRA may also cause a higher number of incidences of the health effects that are part of the model. This is also not captured in this analysis. Thus, the economic value of health effects obtained from COBRA may be interpreted as a conservative estimate of the health benefits from reducing emissions.

C.5 Calculating Environmental Benefits for the TOUGH Series of Reservoir Models and Binary Cycle Plant Technologies

Environmental benefits of the TOUGH series of reservoir models and binary cycle plant technologies are related to the proportion of energy that would have been generated using fossil fuels but was displaced by energy generated by geothermal power plants. Electricity production associated with these two technologies that offset fossil fuels included:

- For binary cycle plants:
  - efficiency gains (binary compared to flash at mid-level temperatures)
  - all low temperature binary plant generation
- For the TOUGH series:
  - all efficiency gains from reservoir modeling

Emissions reductions in air pollutants that result from using geothermal technologies as compared to the next best technology alternative are calculated. EPA’s Co-Benefits Risk Assessment (COBRA) model was used to calculate the health benefits of these reductions in air pollutants (see also Sections 6.3 and 7.3). The steps to calculate these emission reductions and apply them to COBRA are described below.

To calculate the benefits, first, the proportion of each fossil fuel type (coal, petroleum, and natural gas) providing power was reviewed in each state. Four states (California, Nevada, Utah, and Hawaii) account for 99.9% of the geothermal energy produced in the United States with California alone accounting for 87%.

Table C-2. Energy Imported by California

Year	Generation[a] (Megawatthours)	Consumption[b] (Megawatthours)	Difference: Import (Megawatthours)
1990	165,784,909	211,092,922	45,308,013
1991	158,947,642	208,650,489	49,702,847
1992	177,155,459	213,447,241	36,291,782
1993	186,990,642	210,499,926	23,509,284
1994	186,191,991	213,684,302	27,492,311
1995	181,463,341	212,604,724	31,141,383
1996	175,263,204	218,112,485	42,849,281
1997	172,797,595	227,880,126	55,082,531
1998	189,600,706	236,433,970	46,833,264
1999	188,319,223	234,830,879	46,511,656
2000	208,082,483	244,057,202	35,974,719
2001	198,596,075	247,758,778	49,162,703
2002	184,210,031	235,213,332	51,003,301
2003	192,788,542	243,221,316	50,432,774
2004	194,780,355	252,025,973	57,245,618
2005	200,292,818	254,249,507	53,956,689
2006	216,798,688	262,958,528	46,159,840
2007	210,847,581	264,234,911	53,387,330
2008	207,984,263	268,155,219	60,170,956

[a] Source: EIA (2009).
[b] Source: EIA (2010).

California imports approximately 20% of the total energy consumed within the state (see Table C-2). In the absence of geothermal power plants, the next alternative for California would be to buy additional electricity from neighboring states. The World Nuclear Association (WNA) estimates that 43.5% of electricity imported by California comes from the Pacific Northwest and 56.5% from the Southwest (WNA, 2009). The Pacific Northwest includes Washington and Oregon, and the Southwest includes New Mexico, Arizona, and Nevada. This study assumed that imports were composed of marginally generated electricity (i.e., electricity generated by burning fossil fuels – coal, natural gas, and petroleum).

Data on electricity generated per year in each state were added to calculate totals for each region (Pacific Northwest and Southwest). That data were then weighted by the annual amount of electricity imported to California (see Table C-2) and multiplied by the respective share (43.5% for the Pacific Northwest, and 56.5% for the Southwest). Table C-3 presents the outcome of this calculation, as well as the proportion of each fossil fuel type providing power for import to California. These shares are also reported in Table C-4. Table C-4also presents the share of geothermal energy generated by each state and proportion of each fossil fuel type for the other states producing geothermal power.

Table C-3. Weighted Average Fossil Fuel Mix of California Imports (MWh)

Zone	Natural Gas	Coal	Petroleum
Pacific Northwest	5,532,650	15,086,344	51,315
Southwest	13,194,925	13,522,802	153,674
Total	18,727,575	28,609,146	204,989
Percentage share	39.4%	60.2%	0.4%

Source: EIA (2009).

Table C-4. Geothermal Energy Generation and the Offset Mix by Fuel Type by State, 2008

State	Share of Geothermal Energy Produced in the U.S.	Natural Gas	Coal	Petroleum
California[a]	87%	39.4%	60.2%	0.4%
Nevada	11%	44.2%	55.3%	0.5%
Utah	~1%	5.1%	94.8%	0.1%
Hawaii	~1%	—	14.1%	85.9%
Weighted average		39.2%	60.0%	1.3%

Source: EIA (2009).

[a] California Fuel Mix represents the mix in energy California reports from other states (calculated in Table C-3).

The share of geothermal in each state was applied respectively to generation due to binary cycle plants (offsetting fossil fuels) and the tough series of reservoir models to obtain the statewide generation offsets from each of the two technologies. emissions factors shown in Table C-5 were then applied to the average fossil fuel mix offset to obtain emissions reductions. These are thus the emission reductions for pollutants such as PM, NO_x, and SO_2 that result from using the geothermal technologies in lieu of the next best technology. These emission reductions were applied to the respective states in the COBRA model. For California, the reductions were applied to the states from the Pacific Northwest and the Southwest. Generation from each of the states was used to determine the share of emissions reductions that were applied to each state.

Table C-5. Emissions Factors Underlying Health Effects (Avoided Emissions [kg/kWh])

Technology	Natural Gas			Coal		
	PM	SO_2	NO_x	PM	SO_2	NO_x
Binary Cycle						
Offsetting fossil fuel plants	0.0001100	0.0014804	0.0000700	0.0051919	0.0021550	0.0011155
Offsetting geothermal flash plants	NA	NA	NA	NA	NA	NA
TOUGH						
Offsetting fossil fuel plants	0.0000578	0.0014801	0.0000700	0.0051396	0.0021547	0.0011155

Technology	Petroleum			Flash Plants		
	PM	SO_2	NO_x	PM	SO_2	NO_x
Binary Cycle						
Offsetting fossil fuel plants	0.0003568	0.0011670	0.0000297	NA	NA	NA
Offsetting geothermal flash plants	NA	NA	NA	0.0001750	0	0
TOUGH						
Offsetting fossil fuel plants	0.0003045	0.0011667	0.0000297	NA	NA	NA

C.6 References

Abbey, D. E., Ostro, B. E., Petersen, F., & Burchette, R. J. (1995). Chronic respiratory symptoms associated with estimated long-term ambient concentrations of fine particulates less than 2.5 microns in aerodynamic diameter (PM2.5) and other air pollutants. *Journal of Exposure Analysis and Environmental Epidemiology, 5* (2), 137–159.

Abt Associates Inc. (2009, January). *Economic impact of Wise County, Virginia coal-fired power plant*. Prepared for Wise Energy for Virginia Coalition.

Dockery, D. W., Cunningham, J., Damokosh, A. I., Neas, L. M., Spengler, J. D., Koutrakis, P., Ware, J. H., Raizenne, M., & Speizer, F. E. (1996). Health effects of acid aerosols on North American children—Respiratory symptoms. *Environmental Health Perspectives, 104* (5), 500–505.

EIA (Energy Information Administration). (2009). U.S. Electric Power Industry Net Generation. Electric Power Annual with data for 2007. Released January 20, 2009. Washington, DC: U.S. Department of Energy.

EIA (Energy Information Administration). (2010). Retail Sales of Electricity by State by Sector by Provider, 1990-2008. States Historical Tables for 2008. Released January 21, 2010. Washington, DC: U.S. Department of Energy.

Ito, K. (2003). Associations of particulate matter components with daily mortality and morbidity in Detroit, Michigan. In: *Revised analyses of time-series studies of air pollution and health.* Boston, MA: Health Effects Institute.

Moolgavkar, S. H. (2000). Air pollution and hospital admissions for chronic obstructive pulmonary disease in three metropolitan areas in the United States. *Inhalation Toxicology, 12* (Suppl 4), 75–90.

Moolgavkar, S. H. (2003). Air pollution and daily deaths and hospital admissions in Los Angeles and Cook Counties. In: *Revised analyses of time-series studies of air pollution and health*. Boston, MA: Health Effects Institute.

Norris, G., YoungPong, S. N., Koenig, J. Q., Larson, T. V., Sheppard, L., & Stout, J. W. (1999). An association between fine particles and asthma emergency department visits for children in Seattle. *Environmental Health Perspectives, 107* (6), 489–93.

Ostro, B. D. (1987). Air pollution and morbidity revisited: A specification test. *Journal of Environmental Economics and Management, 14,* 87–98.

Ostro, B. D., & Rothschild, S. 1989. Air pollution and acute respiratory morbidity – an observational study of multiple pollutants. *Environmental Research, 50*(2), 238–247.

Peters, A., Dockery, D. W., Muller, J. E., & Mittleman, M. A. (2001). Increased particulate air pollution and the triggering of myocardial infarction. *Circulation, 103* (23), 2810–5. http://www.ncbi.nlm.nih.gov/htbinpost/Entrez/query?db=m&form=6&dopt=r&uid=11401937.

Pope, C. A., 3rd, Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., & Thurston, G. D. (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *Journal of the American Medical Association, 287* (9), 1132–41.

Schwartz, J., & Neas, L. M. (2000). Fine particles are more strongly associated than coarse particles with acute respiratory health effects in schoolchildren. *Epidemiology, 11* (1), 6–10.

Sheppard, L., Levy, D., Norris, G., Larson, T. V., & Koenig, J. Q. (1999). Effects of ambient air pollution on nonelderly asthma hospital admissions in Seattle, Washington, 1987–1994. *Epidemiology, 10* (1), 23–30.

U.S. EPA (Environmental Protection Agency). (2005, March). *Regulatory impact analysis for the final Clean Air Interstate Rule*. EPA-452/R-05-002. Research Triangle Park, NC: Office of Air Quality Planning and Standards; Emission, Monitoring, and Analysis Division and Clean Air Markets Division. Available at http://www.epa.gov/cair/pdfs/finaltech08.pdf.

U.S. EPA (Environmental Protection Agency). (2006, June). *User's manual for the Co-Benefits Risk Assessment (COBRA) screening model*. Developed by Abt Associates Inc.

World Nuclear Association (WNA). December 2009. *California's Electricity*. Available at http://www.world-nuclear.org/info/inf65.html.

APPENDIX D:

GEOTHERMAL R&D PROGRAM FUNDING TIME SERIES

DOE provided a time series of total GTP expenditures with a breakout of appropriation line items from 1976 to 2008. Total GTP expenditures over this time period are shown in Table 4-4 and the total was $2,601 million ($2008). These costs were used in the cluster analysis.

Technology-specific cost estimates were also developed for the four case studies. Note that the individual technology cost estimates do not affect the overall cluster findings but do provide insights into the individual economic return for the four technologies selected.

D.1 Expense Methodology for Case Study Technologies

For **high temperature cement**, DOE cost records were available from 2001 to 2006 (see Table D-1). The annual average of $141,667 was used for the remaining years of the time series from 1976 through 2008, when research was ongoing but cost information was not available.

Table D-1. High-Temperature Cement DOE Costs

Year	Cement Project ($2008)
2001	$150,000
2002	$150,000
2003	$150,000
2004	$120,000
2005	$130,000
2006	$150,000
Annual average	$141,667

For **TOUGH series of reservoir models**, DOE indicated that between two and three FTE were supporting this research between 1976 and 1991. After 1991, the research involved about ½ and FTE. Thus, the following costs were used:

- 1976 to 1991: 2.5 FTEs x $159,000/yr/FTE[1]
- 1991 to 2008: 0.5 FTE x $159,000/yr/FTE

These numbers were multiplied by a factor of 2 to account for overhead expenditures; however, DOE was not able to provide expenditures associated with the **PDC drill bit** and **binary cycle power plant** technologies. Thus, RTI estimated technology-specific expenditures based on the appropriation line items. From 1986 to 2002, appropriation line items were available with sufficient detail to allocate costs to the specific technologies. Table D-2 lists the line items and shares used to build up DOE costs for each of the technologies from 1986 through 2002.

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[1] $159,000/yr/FTE reflects a Ph.D. physicist, 90th percentile wage rate (BLS, 2009).

Table D-2. Budgetary Line Items Used to Develop Technology Costs

Budgetary Line Items by Technology	Years Reported in Time Series
PDC Drill Bit	
Hard rock penetration research[a]	1986–1989
Drilling technology[b]	1994–1998
Binary Cycle Power Plant Technology	
Heat cycle research	1986
Hydrothermal systems[c]	1986; 1988; 1990–1992
Energy conversion technology[c]	1987–1989; 1993–1994; and 1996–1998
Advanced heat & power systems[c]	1999–2002

[a] Assumes 50% of hard rock penetration research funding is associated with PDC drill bits.
[b] Assumes 25% of drilling technology funding is associated with PDC drill bits.
[c] Assumes 25% of hydrothermal systems, 25% energy conversion technology, and 25% of advanced heat power systems funding is associated with binary cycle power plant technology.

Before 1986 and after 2002, funding was appropriated to aggregated research categories, and separate cost information for the four technologies selected for this study was not available. DOE staff indicated that for both technologies associated research was conducted before 1986 and after 2002. Thus, the time series of available technology-specific costs (1986 to 2002) was extrapolated to generate a cost time series from 1976 to 2008.

Table D-3 summarizes the costs used in the analysis.

Table D-3. Allocation of GTP Funding by Technology Category, 1976 –2008 (thousands $2008)

Categories:	Total Costs by Technology	Average Annual Costs	Percentage of Total DOE Costs
PDC drill bit	$63,183	$1,914	3.8%
High-temperature geothermal well cements	$4,675	$142	0.2%
TOUGH series of reservoir models	$15,462	$468	0.6%
Binary cycle power plant technology	$60,311	$1,827	3.6%
Total GTP Costs (Cluster Analysis)	$2,627,966		

D.2 References

Bureau of Labor Statistics (BLS). (May 04, 2009). *Occupational Employment and Wages, May 2008: 19-2012 Physicists. Table: Percentile wage estimates for this occupation.* Washington DC: U.S. Department of Labor. Available at http://www.bls.gov/oes/2008/ may/oes192012.htm#ind

APPENDIX E[1]:

BIBLIOMETRICS METHODOLOGY USED IN THE KNOWLEDGE BENEFITS CHAPTER

This appendix provides a brief treatment of the bibliometric methods of evaluation—particularly patent analysis—used in the source report from which this appendix is derived. For additional information about these and other methods used in the source report, please refer to Ruegg and Thomas, *Linkages from EERE's Geothermal Program R&D to Commercial Power Generation*, 2010.

Bibliometric methods of evaluation tend to be useful in historical tracing studies, such as the source study, which traces from DOE's geothermal R&D to downstream power generation. Bibliometric methods can be used to provide objectively derived, quantitative measures of linkages from publication and patent outputs of the R&D program to other publications and patents outside the program. The related analyses can indicate that knowledge has been created, who created it, the extent that it is being disseminated and used (or at least referenced) by others, and who is using or referencing it.

E.1 Why Patent Analysis?

When looking for connections from knowledge creation in a research program to commercialized technologies, patents are of particular interest because they are considered close to application. The use of patents as indicators of technology creation, and patent citation analysis to locate technology diffusion, reflects the central role of patents in the innovation system. Patent citation analysis has been used extensively in the study of technological change.

In patent analysis, a reference from a patent to a previous patent is regarded as recognition that some aspect of the earlier patent has had an impact on the development of the later patent. In the patent analysis presented in this report, the idea that the technologies represented by patents that cite DOE-supported patents have built in some way on the patents attributable to research funded by DOE.

Patent citation analysis also has been employed in other studies, as it is here, to evaluate the impact of particular patents on technological developments. This approach is based on the idea that highly cited patents (i.e., patents cited by many later patents) tend to contain technological information of particular importance, because they form the basis for many new innovations, they are cited frequently by later patents. Although it is not true to say that every highly cited patent is important, or that every infrequently cited patent is unimportant, research studies have shown a correlation between the rate of citations of a patent and its technological importance.[2]

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[1] This appendix was prepared by Rosalie Ruegg, TIA Consulting Inc. and Patrick Thomas, 1790 Analytics LLC.

[2] For background on using patent citation analysis, including a summary of validation studies supporting its use, see Breitzman A. & Mogee M. "The many applications of patent analysis," *Journal of Information Science, 28* (3), 2002, 187–205. For a similar background on the use of paper citation analysis, see Chapter 3 of Thomas P. "*Fashions in Management Research,*" 1999, Ashgate Press.

E.2 “Prior Art”

A patent discloses to society how an invention is practiced, in return for the right, during a limited period of time, to exclude others from using the patented invention without the patent assignee’s permission. The front page of a patent document contains a list of references to prior art. “Prior art“ refers to all information that previously has been made available publicly such that it might be relevant to a patent’s claim of originality and, hence, its validity. Prior art may be in the form of previous patents, or published items such as scientific papers, technical disclosures, and trade magazines.

Patent citation analysis centers on the links between generations of patents and between patents and scientific papers that are made by these prior art references. In basic terms, this type of analysis is based on the idea that the prior art referenced by patents has had some influence, however slight, on the development of these patents. The prior art is thus regarded as part of the foundation for the later invention.

In assessing the influence of individual patents and papers, citation analysis centers on the idea that highly cited patents/papers (i.e., patents/papers cited by many later patents) tend to contain scientific or technological information of particular interest or importance. As such, they form the basis for many new innovations and research efforts and are cited frequently by later patents.

E.3 Forward and Backward Patent Tracing

Two approaches to patent analysis were used in this study—forward tracing and backward tracing—paralleling the two perspectives of the broader historical tracing framework.

E.3.1 Forward Patent Tracing

The idea of forward tracing is to take a given body of research and to trace the influence of this research on subsequent technological developments. In the context of the current analysis, forward tracing involves identifying all geothermal energy patents and papers resulting from research programs funded by DOE. The impact of these patents and papers on subsequent generations of technology is then evaluated. This tracing is not restricted to later geothermal energy patents, since the influence of a body of research may extend beyond its immediate technology. Hence, the purpose of the forward tracing element of this project is to determine the impact of EERE-funded geothermal energy patents on developments both inside and outside geothermal energy technology.

E.3.2 Backward Patent Tracing

The idea of backward tracing is to take a particular technology, product, or industry and to trace back to identify the earlier technologies on which it has built. In the context of this project, the idea of backward patent tracing is to trace back to identify the earlier technologies on which the geothermal industry has built. To do this required first identifying the set of total geothermal patents. By tracing backward from this total set of geothermal patents to earlier geothermal patents attributed to EERE-funded geothermal R&D, it is possible to determine the extent to which later innovations built on earlier DOE-funded research. Furthermore, comparing the extent of the linkage of the total set back to earlier DOE-attributed patents versus the linkages back to other organizations provides an indication of the relative importance of DOE in establishing a knowledge base on which other organizations built further innovations in geothermal.

E.4 Extensions of the Patent Citation Analysis

The simplest form of patent tracing is based on a single generation of citation links between U.S. patents. Such a study identifies U.S. patents that cite, or are cited by, a given set of U.S. patents as prior art. This study extends the patent analysis in three ways, as discussed below.

E.4.1 Extension to Patents Citing Publications

This study extends the analysis to include patent citations of publications authored by DOE-funded researchers. The rationale for this extension is that DOE scientists may produce publications that are considered directly relevant to a technology's development. Adding prior art references to DOE-supported publications thus takes into account the influence of the research described in these publications on innovations captured in patents.

E.4.2 Extension to Multiple Generations of Citation Links

This study extends the analysis by adding a second generation of citation links. This means that the study traces forward through two generations of citations starting from DOE-supported geothermal energy patents and papers and backwards through two generations starting from the patents of leading geothermal-energy innovating companies.

The idea behind adding this second generation of citations is that federal agencies such as DOE often support scientific research that is more basic than applied. It may take time and multiple generations of research for this basic research to be used in an applied technology, such as that described in a patent. The impact of the basic research may not therefore be reflected in a study based on referencing a single generation of prior art. Introducing a second generation of citations provides greater access to these indirect links between basic and applied research and technology development.

One potential problem with adding a second generation of citations should be acknowledged. This is a problem common to many networks, whether these networks consist of people, institutions, or scientific documents, as in this case. The problem is that, if one uses enough generations of links, eventually almost every node in the network will be linked. By the same logic, if one takes a starting set of patents, and extends the network of prior art references far enough, eventually almost all earlier patents and papers will be linked to this starting set. Based on our previous experience, using two generations of citation links is appropriate for tracing studies such as this; however, adding additional generations may bring in too many patents with little connection to the starting patent and paper sets.

E.4.3 Extension beyond the U.S. Patent System

The report looked beyond the U.S. patent system to include patents from the European Patent Office (EPO) and patent applications filed with the World Intellectual Property Organization (WIPO). The analysis thus allows for a wide variety of possible linkages between DOE-funded geothermal energy research and subsequent technological developments.

E.5 Patent Data Sets for Analysis

The backward tracing elements of the study starts from the set of all geothermal energy patents, while the forward tracing starts from the set of geothermal energy patents attributed to DOE funding. Neither of these data sets existed; both had to be constructed for this the study.

E.5.1 Identifying DOE-Attributed Geothermal Energy Patents for Forward Tracing

Identifying patents funded by government agencies is often more difficult than identifying patents funded by companies. When a company funds internal research, any patented inventions emerging from this research are likely to be assigned to the company itself. To construct a patent set for a company, one simply has to identify all patents assigned to the company, along with all of its subsidiaries, acquisitions etc.

In contrast, a government agency such as DOE may fund research in a variety of organizations. For example, DOE operates a number of laboratories and research centers. Patents emerging from these laboratories and research centers may be assigned to DOE, or they may be assigned to the organization that manages the laboratories or research centers. For example, patents from Sandia may be assigned Lockheed Martin, while Livermore patents may be assigned to the University of California.

A further complication is that DOE does not only fund research in its own labs and research centers. It also funds research carried out by private companies and universities. If this research results in patented inventions, these patents are likely to be assigned to the company or university carrying out the research, rather than to DOE.

To identify geothermal patents resulting from DOE-funded research, the study first searched within the set of patents identified by the geothermal patent filter and matched this patent set to three sources to identify those attributable to DOE funding:

- ***OSTI Database*** – The first source used was a database provided by DOE's Office of Scientific & Technical Information (OSTI) for use in DOE-related projects. This database contains information on research grants provided by DOE since its inception. It also links these grants to the organizations or DOE centers carrying out the research, the sponsor organization within DOE, and the U.S. patents that resulted from these DOE grants.

- ***Patents assigned to DOE*** – The study identified a number of U.S. patents assigned to DOE that were not in the OSTI database because they have been issued since the latest version of that database. These patents were added to the list of DOE-attributed patents.

- ***Patents with DOE Government Interest*** – A U.S. patent has on its front page a section entitled "Government Interest," which details the rights that the government has in a particular invention. For example, if a government agency funds research at a private company, the government may have certain rights to patents granted based on this research. The study identified all patents within the set identified by the geothermal patent filter that refer to "Department of Energy" or "DOE" in their Government Interest field, along with patents that refer to government contracts beginning with DE- or ENG-, since these abbreviations denote DOE grants. Patents in this set that were not in the OSTI database and were not assigned to DOE were added to the list of DOE-attributed patents.

In addition to this procedure, the study identified DOE-attributed geothermal patents found through a search of DOE reports. These reports detail the history of DOE funding in geothermal energy (for example the 2006 report "Geothermal Power Today" http://www.nrel.gov/docs/fy06osti/39479.pdf).

The DOE reports often identify specific geothermal patents resulting from funding by DOE. These patents were added to the DOE-attributed patent set resulting from the geothermal filter. The reports also in some cases identify organizations whose geothermal energy research has been funded by DOE, the period of funding, and technologies funded. By matching the organizations, time periods, and technologies from these documents with patent data, it was possible to identify additional patents from these organizations that are likely to have been funded (at least in part) by DOE, even if they did not formally acknowledge DOE's support.

The next step was to send the list of candidate patents identified through this multistep process to DOE scientists and program managers. They in turn provided feedback on which of the candidate patents should be included in the study's final set of DOE-attributed patents and which should be omitted.

E.5.2 Identifying the Set of All Geothermal Energy Patents for Backward Tracing

To identify the set of all geothermal patents for the backward tracing, the study designed a patent filter. To identify U.S. patents, the filter used a combination of keywords and Patent Office Classifications (POCs). Meanwhile the filter to identify EPO and WIPO patents used a combination of keywords and International Patent Classifications (IPCs). The patent filter consisted of four separate searches, as described in detail in the source report.

Patents identified by any of the four searches were considered for inclusion in the final set of geothermal patents. The titles of all these candidate patents were read individually, and irrelevant patents removed from the set. This resulted in a final geothermal patent set consisting of 871 U.S. patents, 180 EPO patents, and 234 WIPO patents.

The design of the patent filter has important implications for the backward tracing element of the analysis presented in this report. It is this filter that determines which patents are included in the geothermal patent set used as the starting point for this backward tracing. More specifically, keyword restrictions require that a patent must refer specifically to a geothermal, hot rock, or hot spring application in its title or abstract in order to be considered a geothermal patent.

The keyword restriction is included because of the nature of geothermal technology. Some technologies are relatively self-contained, and their patents use unique terminologies. This is not the case with geothermal technology, which shares many similarities with oilfield technology. For example, technologies such as drill bits, downhole sensors, data transmission techniques, and well cements and casings may have applications for both the oilfield and geothermal industries. Including all such patents would swamp the geothermal patents with the much larger set of oilfield patents (for example, there are over 11,000 U.S. patents in POC 175 “Boring or Penetrating the Earth” alone). The keyword restriction is designed to prevent this from happening. The effects of this approach is to produce a conservative estimate of geothermal patents for the backward tracing analysis; one that focuses more on geothermal power plants and geothermal fluid treatments that tend to make specific reference to their geothermal focus.

This highlights the benefit of carrying out the analysis in two directions, since the forward tracing element helps demonstrate DOE’s impact on patents that do not specifically refer to a geothermal application but may be related to geothermal technology.

E.6 Constructing Patent Families Based on the "Priority Application"

Organizations often file for protection of their inventions across multiple patent systems. For example, a U.S. company may file to protect a given invention in the United States and also file for protection of this invention in other countries. Also, inventors may apply for a series of patents in the same country based on the same underlying invention. As a result, there may be multiple patent documents for the same invention. In the case of this project, one or more U.S., EPO, and WIPO patents may result from a single invention.

A search for equivalents of each of the DOE-attributed patents was made in the EPO and WIPO systems to avoid counting patents on the same invention more than once. An equivalent is a patent filed in a different patent system covering essentially the same invention. A search was also made for U.S. patents that are continuations, continuations-in-part, or divisionals of each of these patents. In total, 115 U.S. patents, 16 EPO patents, and 17 WIPO patents were identified.

Patents that are all based on the same underlying invention are constructed into patent families. A patent family contains all of the patents and patent applications that result from the same original patent application (named the priority application). A family may include patents/applications from multiple countries, and also multiple patents/applications from the same country.

For this study, it was necessary to construct patent families for DOE and also for all of the patents/applications linked through citations to DOE. To construct these patent families, the priority documents of the U.S., EPO and WIPO patents/applications were matched, to group them in the appropriate families. Fuzzy matching algorithms were used to achieve this, along with a small amount of manual matching, since priority documents have different number formats in different patent systems. It should be noted that the priority document need not necessarily be a U.S., EPO, or WIPO application. For example, a Japanese patent application may result in U.S., EPO, and WIPO patents/applications, which are grouped in the same patent family because they share the same Japanese priority document.

As a result of this process, the 90 patent families attributed to DOE-funded research were identified, containing U.S., EPO, and WIPO geothermal energy patents/applications. Meanwhile the set of all U.S., EPO, and WIPO geothermal energy patents/applications were grouped into 1,016 patent families.

E.7 Publication Coauthoring and Citation Analyses

Past similar studies suggest that analyses of publications may offer additional insights into the creation and dissemination of knowledge from EERE's geothermal R&D program. The volume of publications over time provides an indication of the extent of publications as a knowledge output. Coauthoring of publications in advanced combustion by EERE researchers with researchers from other organizations may indicate collaboration and links between EERE researchers and researchers involved in downstream technology development and commercialization. Citations of publications resulting from EERE geothermal research show paths of knowledge flow.

The publication citation search is facilitated by using a publication citation database and search engine. For a long period, the U.S.-based firm Thomson Scientific (formerly the Institute for Scientific Information [ISI]) was the principal tool facilitating publication citation analysis. But today a growing number of publication citation databases and search tools, such as Scopus, CiteSeer, and Google Scholar, provide comprehensive coverage beyond the major journals, including, for example, conference proceedings, book chapters, dissertations, and research reports.[3] For this study's publication-to-publication citation analysis, conference papers and research reports were prominent, and Google Scholar was used because it included these kinds of publications in its search capability. A comparison of alternative publication search tools rated Google Scholar among the best.[4]

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[3] Meho, Lokman I. The rise and rise of citation analysis. *Physics World, 20*, 1, 32-36.
[4] Ibid., 31-36.

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