September 2017

Benefit-Cost Evaluation of U.S. Department of Energy Investment in HVAC, Water Heating, and Appliance Technologies

Final Report

Prepared for

Building Technologies Office
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy
1000 Independence Avenue SW
Washington, DC 20585

Prepared by

Michael Gallaher
Troy Scott
Zachary Oliver
Kyle Clark-Sutton
Benjamin Anderson
RTI International
3040 E. Cornwallis Road
Research Triangle Park, NC 27709

Rosalie Ruegg
TIA Consulting

RTI Project Number 0214666

Acknowledgements

The authors wish to thank the many scientists, engineers, and analysts who contributed data and insights that informed this evaluation. We are especially grateful to two external reviewers, Irwin Feller and Cheryl Oros, and to internal DOE reviewer Sam Baldwin. John Ryan provided a wealth of information on BTO's Building Equipment R&D portfolio. Jack Mayernik, Mark Friedrichs, Yaw Agyeman, Tony Bouza, and Jeff Dowd were the project managers overseeing RTI's technical performance for DOE-EERE.

Notice

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, usefulness or any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Contents

Figures

Tables

Executive Summary

The purpose of this study is to conduct a rigorous benefit-cost impact evaluation of the research and development (R&D) activities of the Building Technologies Office (BTO) in the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE). The study focuses on one of four long-standing R&D portfolios within BTO's Emerging Technologies Program: R&D investments in heating, ventilation, and air conditioning (HVAC), water heating, and appliance technologies.

This evaluation answers the question of whether BTO's investments in HVAC, water heating, and appliance technologies have been worthwhile. The analysis suggests that they have indeed, generating benefits 20 to 66 times R&D portfolio costs and providing an estimated internal rate of return of between 38% and 51%.

BTO's mission is to improve the energy efficiency of United States homes and buildings through a combination of energy performance standards, building energy codes, and R&D investments. The purpose of this analysis is to evaluate the performance of only the R&D investments, asking the question: Have BTO investments in HVAC, water heating, and appliance R&D generated a reasonable rate of return on investment?

The analysis suggests that the answer is yes. Considering only energy and resource benefits—that is, the economic value of energy savings attributable to BTO R&D—the estimated benefit-to-cost ratio is between 20-to-1 and 66-to-1, using a 7% discount rate; the estimated internal rate of return is between 38% and 51%.

Interviews with industry experts point to several reasons BTO R&D has had these impacts. DOE laboratories are perceived by industry to be trusted independent sources of objective, scientific and engineering data and fundamental knowledge. The research output of DOE laboratories is valuable to industry because the laboratories combine objectivity—a reputation as a trusted third party—with solid technical capabilities and state-of-the-art facilities, such as HVAC and refrigeration test facilities. DOE laboratories integrate multidisciplinary scientific and engineering capabilities that are beyond the scope of most companies' R&D laboratories. BTO R&D investments are able to leverage these facilities and interdisciplinary expertise to conduct basic research having applications much broader than

BTO R&D investments support the role of DOE laboratories as trusted third-party sources of objective, high-quality scientific and engineering data and research. BTO R&D impacts stem from its ability to leverage DOE laboratories' unique capabilities to create productive R&D investment opportunities for the private sector.

the scope of any one company's business model. BTO R&D investments can also support early development of novel technologies that companies would find unattractive because of high technical risk (the risk of failing to achieve performance improvements over existing technologies), market risk (the risk of failing to commercialize a product embodying the new technology once it has been successfully developed from a technical perspective), and a long and uncertain timeline to eventual commercialization and market acceptance. Especially high-risk and long-term R&D projects are good candidates for BTO investment because they are less likely to attract private-sector investment.

BTO R&D can de-risk a new energy-efficient technology to the point that a company will want to invest in its further commercial development. BTO's role in the development of a given technology may vary; depending on the technology, its application, and market and other conditions, BTO involvement may end with basic research or proof of concept, or it may extend through later stages of development. BTO investment is most effective when it complements private investment, i.e., when BTO outputs create productive investment opportunities for the private sector, thereby crowding in private investment. The nature of high-risk R&D portfolios is that not all projects will be successful. In selecting projects, the questions to ask are whether a project is one that BTO is uniquely capable of undertaking—a project which the private sector could not or would not choose to undertake—and whether, if it is technically successful, the project will create productive investment opportunities for U.S. industry while advancing BTO's mission.

ES.1 PORTFOLIO APPROACH

The analysis compares R&D investment costs for BTO's HVAC, water heating, and appliance technology portfolio from 1976 through 2015 against the benefits, attributable to those BTO investments, in three technology areas:[1]

1. **flame-retention-head oil burners**, efforts known as Project Oilheat, in which BTO conducted technical research (testing fuel savings and verifying safety and reliability of retrofits) and market conditioning activities (disseminating

[1] DOE was established on October 1, 1977. The analysis includes investments in building technologies made by DOE's predecessor agencies in 1976 and the beginning of 1977.

test results, partnering with states' energy offices and oil dealer trade associations in communications campaigns and technician training), from 1979 to 1981;

2. **advanced refrigeration**, focusing on BTO's research related to the energy-efficiency of residential refrigerators;
3. **heat pump design model and alternative refrigerants research**, including BTO's R&D related to the energy-efficiency of heat pump and air conditioning technology.

Benefits are quantified for three technology areas within BTO's HVAC, water heating, and appliance R&D portfolio:

1. Flame-retention-head oil burners

2. Advanced refrigeration technology

3. Heat pump design model and alternative refrigerants research

These three technology areas were selected from a larger portfolio of R&D investments made by BTO in HVAC, water heating, and appliance technologies, which is one of four long-standing R&D portfolios within BTO's Emerging Technologies Program. The other three portfolios in the Emerging Technologies Program address the technology areas of 1) lighting, 2) windows and building envelope, and 3) building energy modeling.[2] In addition to the three technology areas selected for this evaluation, the HVAC, water heating, and appliance portfolio has included such other technology areas as thermally activated heat pumps, combustion and thermal distribution, and household appliances like dishwashers and clothes washers and dryers.

The portfolio approach to benefit-cost analysis, which we adopt here, compares the economic benefits of only a subset of the portfolio with the investment costs of the entire portfolio. In this case, investment costs include all HVAC, water heating, and appliance R&D investments from 1976 through 2015. The quantified benefits stem from the three selected technology areas as follows:

1. Benefits attributable to BTO's flame-retention-head oil burner investments were quantified in terms of residential heating oil saved by the earlier adoption of flame-retention burners that can be attributed to those investments.
2. Benefits attributable to BTO's R&D investments in advanced refrigeration were quantified in terms of the energy saved by the more rapid improvement in the average energy consumption of residential refrigerators that can be attributed to those R&D investments.

[2] More recently, BTO has added R&D portfolios addressing sensors and controls and transactive energy.

3. Benefits attributable to BTO's R&D investments in heat pumps and air conditioning technology, focusing especially on the heat pump design model and alternative refrigerants research, were quantified in terms of the energy saved by the more rapid improvement in the average energy efficiency of residential heat pumps and central air conditioners.

Benefits attributable to BTO's R&D investments in the three selected technology areas are compared to investment costs for the entire HVAC, water heating, and appliance R&D portfolio, yielding conservative estimates of the overall performance of the portfolio.

Considering only these benefits, BTO's R&D investments have been worthwhile. Combined, these benefits compare favorably with BTO's HVAC, water heating, and appliance R&D investment costs through 2015. Specifically, these investments are estimated to have generated present-valued benefits of between 20 and 66 times their costs (using a 7% discount rate) and an internal rate of return of between 38% and 51%.

Of course, the benefits quantified for this study are not all of the benefits attributable to the HVAC, water-heating, and appliance R&D portfolio, because these are by no means the only technologies supported by these R&D investments. Therefore, the portfolio approach used here yields a conservative estimate of the overall performance of the portfolio, which should therefore be considered a lower bound.

ES.2 COUNTERFACTUAL APPROACH

The analysis endeavors to isolate benefits attributable to BTO R&D investments and include only those among the quantified benefits used to calculate investment performance metrics. This was done through 91 in-depth interviews with experts with knowledge of BTO R&D contributions, industry trends, and other relevant factors. These experts were asked to characterize what would have most likely happened in the absence of BTO R&D, holding all other factors constant.

In principle, the benefits attributable to BTO R&D can be calculated by comparing actual observed trends to the counterfactual trends characterized by these experts. In practice, it is a difficult exercise for someone to "hold all other factors constant" and describe what would have happened without BTO R&D. For this reason, great care was taken to explain the exercise and discuss with the experts a range of factors contributing to the relevant trends in each of the three technology areas.

Estimated benefits attributable to BTO's R&D investments were based on in-depth interviews in which industry experts were asked to characterize what would have happened without BTO R&D. Care was taken to hold constant a range of other factors in order to isolate the impact of BTO R&D investments.

Special attention was paid to the treatment of energy performance standards. Because BTO R&D could have affected the timing and levels of new standards, it would not necessarily be appropriate to hold those factors constant. Experts were therefore asked to hold constant the framework within which standards are developed and promulgated and characterize counterfactual trends without BTO R&D. If the absence of BTO R&D would, in the expert's opinion, have had an effect on the timing or levels of standards, then that would be reflected in her response. In this way, the impact of the standards program is to some extent excluded and the impact of the R&D is isolated. To be sure, the R&D program and the standards program are complementary; on this point experts were unanimous. Therefore, the benefits attributed to BTO R&D are partly due to the standards program, in the sense that BTO R&D would not have been as impactful had the standards programs not existed. However, the purpose of this evaluation was not to quantify the impact of the standards program. Rather, our remit was to isolate, to the extent practicable, the impacts attributable to BTO R&D.

The thought exercise experts were asked to perform in interviews to establish the counterfactual is unavoidably subjective. Nevertheless, this was determined to be the best practicable approach. The alternative to going through this exercise would have been to make some ad hoc assumptions about what would have happened without BTO R&D. We deferred instead to experts' opinions over our own ad hoc assumptions to characterize these counterfactual trends. The purpose of the exercise is to recognize that some improvement in energy efficiency trends—or some development and diffusion of more energy-efficient technologies—might have happened without the BTO R&D and to reduce estimates of attributable benefits accordingly. We offer a wide range of estimated benefits, which appropriately reflects the unavoidable subjectivity inherent in this approach and the variability of experts' opinions.

ES.3 ENERGY AND RESOURCE BENEFITS

BTO R&D is estimated to have saved between 2.2 billion and 5.4 billion gallons of #2 heating oil and between 324,200 and 1,235,891 GWh of electricity, a combined savings of between

1.4 and 5.0 quads, through 2015.[3] To put this in perspective, U.S. households consumed 10.2 quads in 2009: 4.2 quads for space heating; 1.8 quads for water heating; 0.64 quads for air conditioning; 0.48 quads for refrigeration; and 3.0 quads for lighting, appliances, and other residential consumption.[4]

Based on these energy savings, BTO's investments have had a net present value (NPV) of between $6 billion and $22 billion and a benefit-to-cost ratio of between 20-to-1 and 66-to-1 (using a 7% discount rate), and an internal rate of return of between 38% and 51% (Table ES-1).

Table ES-1. Retrospective Investment Performance Metrics: Energy and Resource Benefits

Metric	Low	Mid	High
NPV (millions of 2015 dollars)			
7% Discount Rate	6,205	13,874	21,804
3% Discount Rate	17,820	40,912	64,945
Benefit-to-Cost Ratio			
7% Discount Rate	20:1	42:1	66:1
3% Discount Rate	37:1	84:1	132:1
Internal Rate of Return	38%	46%	51%

Note: Benefits are retrospective; only energy savings realized through 2015 are included.

ES.4 ENVIRONMENTAL HEALTH BENEFITS

The U.S. Environmental Protection Agency's (EPA's) Co-Benefits Risk Assessment (COBRA) model was used to provide first-order estimates of avoided adverse health events and their economic value, termed environmental health benefits, resulting from avoided air emissions.

With the value of these environmental health benefits included, BTO's investments have had a NPV of between $10 billion and $34 billion and a benefit-to-cost ratio of between 30-to-1 and 102-to-1 (using a 7% discount rate), and an internal rate of return of between 46% and 61% (Table ES-2).

[3] One quad is equal to 10^{15} (a short-scale quadrillion) British Thermal Units (BTUs).

[4] Source: U.S. Energy Information Administration, Office of Energy Consumption and Efficiency Statistics, Consumption and Expenditures Table 3.1, 2009 Residential Energy Consumption Survey: https://www.eia.gov/consumption/residential/data/2009/.

Table ES-2. Retrospective Investment Performance Metrics: Energy and Resource Benefits and Environmental Health Benefits

Metric	Low	Mid	High
NPV (millions of 2015 dollars)			
7% Discount Rate	9,698	21,512	33,698
3% Discount Rate	28,034	63,863	101,039
Benefit-to-Cost Ratio			
7% Discount Rate	30:1	65:1	102:1
3% Discount Rate	58:1	130:1	205:1
Internal Rate of Return	46%	55%	61%

Note: Energy and resource benefits are retrospective; only energy savings realized through 2015 are included. Environmental health benefits include benefits realized after 2015 that are associated with energy savings (and commensurate reductions in pollution) realized through 2015. For example, the impacts of reduced pollution in 2015 include incremental reductions in numbers of deaths and nonfatal heart attacks in future years.

ES.5 CONSIDERING REMAINING EFFECTIVE USEFUL LIFE BENEFITS

The inclusion of benefits to reflect remaining effective useful life (EUL) of purchased and installed systems is an extension of the retrospective analysis, in that these are future benefits that have not yet been realized but which are reasonably assured to be realized in the future.

For this analysis, because BTO efforts related to flame-retention-head oil burners were limited to the period from 1977 to 1981, actual and counterfactual trends in the adoption of flame-retention-head oil burners converged by 2010, so this technology area contributes nothing to the EUL analysis. However, because BTO R&D related to advanced refrigeration and heat pumps has been ongoing, attributable benefits are embodied in recently installed refrigerators, heat pumps, and central air conditioners. The retrospective analysis considered only energy savings estimated to have occurred through 2015. The EUL analysis considers also energy savings projected to occur over the remaining life of the equipment, assumed to be 15 years for refrigerators, heat pumps, and central air conditioners. Only equipment that was in use in 2015 is included in the EUL analysis; equipment purchased in 2016 or later is excluded, and no projected equipment sales are included.

When the remaining EUL years are considered for residential refrigerators, heat pumps, and central air conditioners, BTO's investments have a NPV of between $7 billion and $26 billion and a benefit-to-cost ratio of between 23-to-1 and 79-to-1 (using a 7% discount rate), and an internal rate of return of between 38% and 51% (Table ES-3).

Table ES-3. EUL Investment Performance Metrics: Energy and Resource Benefits

Metric	Low	Mid	High
NPV (millions of 2015 dollars)			
7% Discount Rate	7,252	16,455	26,058
3% Discount Rate	23,613	55,196	88,496
Benefit-to-Cost Ratio			
7% Discount Rate	23:1	50:1	79:1
3% Discount Rate	49:1	113:1	180:1
Internal Rate of Return	38%	46%	51%

Note: Benefits associated with residential refrigerators, heat pumps, and central air conditioners include products purchased through 2015, including estimated savings after 2015 during the products' effective useful lives (assumed to be 15 years). In comparison to Table ES-1, the internal rates of return change only slightly, because of the leverage of these high discount rates applied over more than 40 years, and round to the same whole percentage values.

With environmental health benefits included in the EUL analysis, BTO's investments have a NPV of between $11 billion and $39 billion and a benefit-to-cost ratio of between 34-to-1 and 116-to-1 (using a 7% discount rate), and an internal rate of return of between 46% and 61% (Table ES-4).

Table ES-4. EUL Investment Performance Metrics: Energy and Resource Benefits and Environmental Health Benefits

Metric	Low	Mid	High
NPV (millions of 2015 dollars)			
7% Discount Rate	10,911	24,501	38,624
3% Discount Rate	34,854	80,678	128,763
Benefit-to-Cost Ratio			
7% Discount Rate	34:1	74:1	116:1
3% Discount Rate	71:1	164:1	261:1
Internal Rate of Return	46%	55%	61%

Note: Benefits associated with residential refrigerators, heat pumps, and central air conditioners include products purchased through 2015, including estimated savings after 2015 during the products' effective useful lives (assumed to be 15 years), plus the value of avoided adverse health impacts from pollution reductions associated with those energy savings. In comparison to Table ES-2, the internal rates of return change only slightly, because of the leverage of these high discount rates applied over more than 40 years, and round to the same whole percentage values.

ES.6 ROBUSTNESS

We consider the sensitivity of estimated benefits and investment performance metrics to changes in

- the composition of the group of expert informants with whom we spoke,
- assumptions about the average incremental energy efficiency improvement of flame-retention-head oil burners, and
- assumptions about the magnitude of the rebound effect for all three technology areas.

Based on these sensitivity analyses, the main finding is quite robust. Recall, taking the most restrictive estimate of benefits—considering only retrospective benefits for the three technology areas selected from the larger HVAC, water heating, and appliance R&D portfolio and omitting environmental health benefits—the estimated benefits-to-costs ratio is between 20-to-1 and 66-to-1 (Table ES-1). In alternative scenarios based on the most conservative alternative assumptions considered for the sensitivity analysis (Sections 9.1 through 9.4), more than half of the estimated benefits remain, strongly supporting the conclusion that BTO investments in HVAC, water heating, and appliance R&D have been worthwhile.

Scenario analyses show that more than half of estimated benefits remain even under the most conservative alternative assumptions. Applying these assumptions to the lower-bound benefits estimates would still result in estimated benefits of more than ten times R&D investment costs, strongly supporting the conclusion that BTO investments in HVAC, water heating, and appliance R&D have been worthwhile.

This conclusion appears all the more robust in light of the following reasons to view the investment performance metrics as conservative lower bounds:

- The portfolio approach, taken here, considers the investment cost of the entire HVAC, water heating, and appliance R&D portfolio from 1976 (including investments made by DOE's predecessor agencies) through 2015, yet includes estimated benefits for only three technology areas within this portfolio.
- The retrospective energy and resource benefits, which are the basis for the top-line investment performance metrics, do not include environmental health benefits or benefits associated with the remaining EUL of equipment operating as of 2015 but due to accrue in 2016 and later.
- Benefits associated with the knowledge generated by BTO R&D, rated as the most important aspect of BTO's contributions by the experts with whom we spoke, are not quantified beyond their effects on energy efficiency of residential refrigerators, heat pumps, and air conditioners. Knowledge benefits are treated only qualitatively, in an analysis of patenting and patent citations.

For these reasons, a benefits-to-costs ratio of 20-to-1 is appropriately viewed as a lower bound on the estimated performance of BTO investments in HVAC, water heating, and appliance R&D.

1 Introduction

Benefits are quantified for three technology areas within BTO's HVAC, water heating, and appliance R&D portfolio:

1. Flame-retention-head oil burners

2. Advanced refrigeration technology

3. Heat pump design model and alternative refrigerants research

The purpose of this study is to conduct a rigorous benefit-cost impact evaluation of the research and development (R&D) activities of the Building Technologies Office (BTO) in the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE). BTO's mission is to improve the energy efficiency of United States homes and buildings through a combination of energy performance standards, building energy codes, and R&D investments. The sole focus of this study is the R&D aspect of this mission. The study evaluates the performance of one of four long-standing R&D portfolios within BTO's Emerging Technologies Program:[5] R&D investments in heating, ventilation, and air conditioning (HVAC), water heating, and appliance technologies.

The analysis compares R&D investment costs for BTO's HVAC, water heating, and appliance technology portfolio from 1976 through 2015 against the benefits, attributable to those BTO investments, in three technology areas:[6]

1. **flame-retention-head oil burners**, efforts known as Project Oilheat, in which BTO conducted technical research (testing fuel savings and verifying safety and reliability of retrofits) and market conditioning activities (disseminating test results, partnering with states' energy offices and oil dealer trade associations in communications campaigns and technician training), from 1979 to 1981;

[5] The Emerging Technologies Program was called Technology and Consumer Products prior to the 1990s. Beginning in fiscal 2018, the program will be renamed Building Energy Research and Development.

[6] DOE was established on October 1, 1977. The analysis includes investments in building technologies made by DOE's predecessor agencies in 1976 and the beginning of 1977.

2. **advanced refrigeration**, focusing on BTO's research related to the energy-efficiency of residential refrigerators;
3. **heat pump design model and alternative refrigerants research**, including BTO's R&D related to the energy-efficiency of heat pump and air conditioning technology.

These three technology areas were selected from a larger portfolio of R&D investments made by BTO in HVAC, water heating, and appliance technologies, which is one of four long-standing R&D portfolios within BTO's Emerging Technologies Program. The other three portfolios in the Emerging Technologies Program address the technology areas of 1) lighting, 2) windows and building envelope, and 3) building energy modeling. In addition to the three technology areas selected for this evaluation, the HVAC, water heating, and appliance portfolio has included such other technology areas as thermally activated heat pumps, combustion and thermal distribution, and household appliances like dishwashers and clothes washers and dryers.

Benefits attributable to BTO's R&D investments in the three selected technology areas are compared to investment costs for the entire HVAC, water heating, and appliance R&D portfolio, yielding conservative estimates of the overall performance of the portfolio.

By focusing the quantitative benefits analysis on these three technology areas within BTO's HVAC, water heating, and appliances R&D portfolio and comparing estimated benefits to the cost of the entire portfolio, the analysis provides a conservative overall estimate of the portfolio's performance. The appropriateness of this "portfolio approach," as it is called, relies on the fact that a relatively small share of projects in high-risk R&D portfolios typically account for most of the benefits.[7] Projects destined for success cannot be identified at the time they are funded, and so a successful portfolio is one in which the rates of return on successful projects are large enough to also cover the costs of projects that do not achieve technical or commercial success. A retrospective evaluation can therefore select projects that are generally recognized to have been successful, quantify their benefits, and compare these benefits to the investment cost of the entire portfolio.

[7] R&D is inherently risky; not every project is destined for technical or commercial success. Scherer and Harhoff (2000), for example, document highly skewed distributions of returns in eight datasets on inventions and innovations attributable to private sector firms and universities. The top 10% of projects captured between 48% and 93% of returns.

In this case, investment costs include all HVAC, water heating, and appliance R&D investments from 1976 through 2015. The quantified benefits stem from the three selected technology areas as follows:

1. Benefits attributable to BTO's flame-retention-head oil burner investments were quantified in terms of residential heating oil saved by the earlier adoption of flame-retention burners that can be attributed to those investments. For this technology, benefits were quantified based on the faster adoption of a given technology enabled by BTO, rather than on the rate or magnitude of improvement in energy efficiency.

2. Benefits attributable to BTO's R&D investments in advanced refrigeration were quantified in terms of the energy saved by the more rapid improvement in the average energy consumption of residential refrigerators that can be attributed to those R&D investments. For this technology area, benefits were quantified based on the accelerated rate of improvement in the average energy performance of an entire class of products, comprising multiple technologies, rather than on the rate of adoption or energy efficiency of any discrete technology (like, e.g., a refrigerator compressor or motor).

3. Benefits attributable to BTO's R&D investments in heat pumps and air conditioning technology, focusing especially on the heat pump design model and alternative refrigerants research, were quantified in terms of the energy saved by the more rapid improvement in the average energy efficiency of residential heat pumps and central air conditioners that can be attributed to those R&D investments. For this technology area, as with advanced refrigeration, benefits were quantified based on the accelerated rate of improvement in the average energy performance of an entire class of products, comprising multiple technologies, rather than on the rate of adoption or energy efficiency of any discrete technology (like, e.g., a compressor or heat exchanger).

Considering only these benefits, we find the overall investment performance of BTO's HVAC, water heating, and appliance R&D portfolio to be excellent, having generated a benefit-to-cost ratio of at least 19-to-1. By foregoing estimation of benefits associated with other technology areas within the larger portfolio while including all investment costs, the portfolio approach yields a conservative estimate of the overall performance of BTO R&D investments, which should therefore be considered a lower bound.

BTO's HVAC, water heating, and appliance R&D portfolio includes numerous technologies for which benefits were not quantified as part of this study. The portfolio also includes technologies that were recently commercialized and that are therefore only beginning to have impacts that would be quantified here.

To better appreciate why the estimates of investment performance presented here are lower bounds, we refer the reader to the report recently released by BTO, which highlights 27 technologies and 112 LED lighting components that BTO helped to develop and that resulted in commercial products between 2010 and 2015 (U.S. DOE, 2017). While not all of the investment costs associated with these technologies are included in this analysis (the cost of lighting, windows and building envelope, and building energy modeling R&D costs are not included), all HVAC, water heating, and appliance technology R&D costs are included even though most of the benefits of these technologies will accrue in the future and are therefore not quantified here.

For example, the impact of the following small subset of technologies is only beginning to be reflected in the shipments-weighted average energy efficiencies of residential refrigerators, heat pumps, and air conditioners, and is therefore showing up as only a small fraction of the benefits estimated in this analysis:

- Preserva advanced sequential dual evaporator cycle for refrigerators, commercialized by Whirlpool in 2013;
- Everest polyolesters, next-generation refrigerant lubricants, commercialized by Chemtura in 2013;
- Wireless remote monitoring systems and controls for residential air conditioners and heat pumps, commercialized by Mainstream Engineering Corporation in 2014 and 2015;
- Advansor high-efficiency, low-emission refrigeration system, commercialized by Hillphoenix in 2014;
- Solstice N40, a low-global-warming refrigerant, commercialized by Honeywell in 2014.

These technologies, having been only recently commercialized, contribute little to a retrospective evaluation like this one; the majority of their benefits will be realized in the future. Nevertheless, all BTO R&D investment costs associated with these technologies are included in this analysis.

The remainder of the report is organized as follows. Section 2 describes the methodology. Sections 3, 4, and 5 each focus on one of the three selected technology areas: Section 3 on flame-retention-head oil burner, Section 4 on advanced refrigeration, and section 5 on the heat pump design model and alternative refrigerants research. Section 6 looks at a fourth technology area, which was not included in the quantitative analysis but which is a promising area for future impact analysis: water heating technology and especially heat pump water heaters. Section 7 collects the quantified benefits for the three selected technology areas and compares them with BTO R&D investment costs to develop the main investment performance metrics. Section 8 extends the retrospective analysis by also considering the remaining effective useful life of equipment installed and operating as of 2015. Section 9 concludes with a discussion of the robustness of our finding that BTO R&D investments have been worthwhile, based on sensitivity and scenario analyses.

2 Methodology

This study identifies and documents four categories of benefits:

- energy and resource,[8]
- environmental health,
- energy security, and
- knowledge.

Energy and resource benefits are related to the value of goods and services in the economy and include energy-related savings. Advancements in technology are one avenue through which economic benefits increase. Economic benefits accrue to society through the improved performance of existing goods and services and/or through reductions in the cost of existing goods and services. Resource savings, such as energy savings, labor savings, capital savings, or material savings, are often significant sources of economic benefit. The largest source of economic benefits quantified in this study is energy savings.

Environmental benefits are principally changes in pollutant emissions associated with changes in the physical units of fossil-fuel energy consumed. Given the relationship between pollution and environmental health, another stream of economic benefits may accrue through a reduction in the incidence of adverse health events. These are termed environmental health benefits. Environmental health benefits may result from emissions changes related to changes in fossil fuel combustion.

Energy security benefits refer to the changes in risks to the national energy infrastructure, national energy independence, and exposure to exogenous (non-U.S.) volatility in fossil fuel trade.

[8] Although energy is an economic resource, the term *energy and resource* is used in this evaluation given EERE's mission.

Knowledge benefits are derived from the creation and dissemination of explicit knowledge as codified in patents, publications, relational networks, and tacit knowledge traceable to BTO R&D.

Economic benefits for fuel savings and environmental health resulting from BTO R&D are quantified in monetary terms in this evaluation. Energy security and knowledge benefits are described in quantitative and qualitative ways, but not in monetary terms per DOE/EERE impact evaluation guidelines (Ruegg, O'Connor, and Loomis, 2014).

The first three categories of benefits follow a hierarchy. Energy and resource benefits—namely energy savings attributed to BTO R&D—are estimated first. Environmental health benefits and energy security benefits are then calculated based on those estimates. Estimates of energy savings attributable to BTO R&D thus form the foundation of the quantitative part of the analysis and yield the benefits used to develop the main investment performance metrics. These estimates were developed through an extensive primary data collection effort, involving 91 in-depth interviews with experts having knowledge of BTO R&D contributions, industry trends, and other relevant factors for each of the three technology areas.

- Section 2.1 describes our approach to energy and resource benefits estimation, including our primary data collection protocol and our approach to isolating benefits attributable to BTO R&D.
- Section 2.2 describes our approach to environmental health benefits estimation.
- Section 2.3 describes our approach to energy security benefits estimation.
- Section 2.4 describes our approach to knowledge benefits analysis
- Section 2.5 discusses investment performance metrics.
- Section 2.6 discusses selection of technologies for benefits estimation.

2.1 APPROACH TO ENERGY AND RESOURCE BENEFITS ESTIMATION

Economic benefits were measured in terms of the energy savings associated with the BTO's R&D contributions to the development and adoption of three technologies: flame-retention-head oil burners (with energy savings in terms of No. 2 heating oil saved), residential refrigerators, and residential heat pump and central air conditioning systems (with energy savings in terms of electricity saved). The monetized value of energy savings is the principal economic benefit to society associated with BTO's R&D investments. These energy-savings benefits are captured partly by consumers in the form of consumer surplus and partly by firms in terms of producer surplus (i.e., the generally higher profit margins on the most efficient products).

Estimated benefits attributable to BTO's R&D investments were based on in-depth interviews in which industry experts were asked to characterize what would have happened without BTO R&D. Care was taken to hold constant a range of other factors in order to isolate the impact of BTO R&D investments.

Here we discuss our approach to the expert informant interviews on which BTO-attributable impact estimates were based. We first describe the group of experts with whom we spoke. We then describe steps taken to ensure that the benefits estimated based on experts' views and opinions were limited to those that experts would attribute to BTO R&D and not to other contributing factors. In this discussion, we pay special attention to how impacts attributable to BTO R&D are distinguished from impacts attributable to energy performance standards. We describe our characterization of the "next-best technology alternative" for each of the three selected technologies and discuss our rationale for focusing on market diffusion trends, in the case of flame-retention-head oil burners, and shipments-weighted average energy efficiency of residential products, in the case of advanced refrigeration and alternative refrigerants research and heat pump design model.

2.1.1 Primary Data Collection Protocol

Expert informant interviews formed the basis of our analysis. Interviews were conducted with individuals having first-hand knowledge of one or more of the following aspects relevant to BTO's contributions to energy efficiency of HVAC and appliance technologies:

- The relevant BTO research activities

- R&D performed by private companies—both original equipment manufacturers (OEMs) and component manufactures
- Energy performance standards and the process by which new standards are promulgated.
- Relevant activities of industry associations, such as the Association of Home Appliance Manufacturers (AHAM) and Air-Conditioning, Heating, and Refrigeration Institute (AHRI), and advocacy groups, such as the American Council for an Energy-Efficient Economy (ACEEE) and Appliance Standards Awareness Project.
- Relevant activities of other government agencies, such as the U.S. Environmental Protection Agency (EPA) and the National Institute of Standards and Technology (NIST).
- Relevant industry trends.

Through these interviews, we gathered qualitative insights on the way in which BTO contributed to energy efficiency trends, and we gathered quantitative responses that enabled us to estimate the range of impacts that can be attributed to BTO. The qualitative component is intended to at least partly address the concern of Feller (2017) that evaluations like this one address not only the worth, or efficiency, of R&D investments but also provide DOE-EERE with greater insight into impact pathways, to inform the planning and management of future R&D activities.

Names of potential interview participants came from several sources including the following:

- RTI's independent research of industry conference proceedings, publications, regulatory documents such as Energy Star stakeholder meeting summaries, and industry associations such as ASHRAE technical committee. The following sources were especially helpful:
    - ACEEE Summer Study on Energy Efficiency, papers and proceedings from multiple years
    - ASHRAE Reach-in meeting minutes
    - Energy Star stakeholder meeting minutes

  - Heat Pump Design Model Technical Documentation

- Referrals from experts interviewed
- Contacts embedded in program document and reports provided by BTO, and names provided by BTO.

The majority of persons contacted were drawn from RTI's independent research (Table 2-1). From all sources, we identified 397 potential contacts from 239 organizations. We were able to obtain contact information for 231 individuals, and we interviewed 91 individuals representing a total of 65 organizations (Table 2-2). The conditional probability of an individual being interviewed, conditional on their being identified as a potential interviewee, is significantly lower for potential contacts identified by RTI. The main reason is that these potential interviewees were much less likely to have contact information. The possible effects of this issue on our estimates of BTO-attributable impacts are discussed in Section 9, where sensitivity and scenario analyses are presented.

Table 2-1. Sources of Potential Interviewees

	Source of Potential Interviewee				
Stakeholder Group	**RTI**	**Respondent Referral**	**ORNL**	**BTO**	**Total**
Manufacturer	112	15	24	5	156
National Lab	16	7	0	9	32
Federal Agency	17	1	1	1	20
University	40	7	3	1	51
Industry/Trade Association	14	6	2	3	25
Advocacy Group	23	9	1	1	34
Consulting	6	0	3	1	10
Other	62	6	0	1	69
Total	290	51	34	22	397

Note: Names obtained from multiple sources are reported under the source with the fewest names: BTO first, then Oak Ridge National Laboratory (ORNL), then respondent referral, then RTI.

Table 2-2. Sources of Actual Interviewees

Stakeholder Group	Source of Potential Interviewee				
	RTI	Respondent Referral	ORNL	BTO	Total
Manufacturer	8	7	16	3	34
National Lab	4	6	0	6	16
Federal Agency	4	1	0	1	6
University	6	3	2	0	11
Industry/Trade Association	3	4	0	3	10
Advocacy Group	1	6	1	0	8
Consulting	0	0	2	0	2
Other	0	3	0	1	4
Total	26	30	21	14	91

Note: Interviewees whose names we obtained from multiple sources are reported under the source with the fewest names: BTO first, then ORNL, then respondent referral, then RTI.

2.1.2 Attribution of Benefits to BTO R&D

The nature and magnitude of impacts attributable to BTO R&D were assessed through detailed interviews with informed industry experts and scientists and engineers at DOE laboratories. Ideally, the BTO-attributed impact is assessed by comparing actual observed outcomes with the counterfactual outcomes that would have been observed in the absence of BTO R&D. But the counterfactual outcomes cannot be observed, and it is not realistic to design a randomized, controlled experiment to identify the BTO impact.

We are therefore compelled to rely on expert opinions to characterize the counterfactual outcomes and thus reveal the BTO impact. In interviews, we asked experts to characterize what would have most likely happened in the absence of BTO R&D, holding all other factors constant. Because of the many other factors influencing observed outcomes (e.g., energy performance standards programs, private R&D and commercialization efforts by companies, the research and regulatory activities of other government agencies like EPA and NIST), this is a difficult thought experiment for interviewees to perform. At best, we can expect to capture what is, based on interviewee’s perspectives and opinions, a reasonable range for the impacts that can be fairly attributed to BTO research.

To ensure that variation among interviewee’s responses reflects, as nearly as possible, only true differences of opinion regarding BTO’s impact, we took the following steps when conducting interviews:

1. Interview guides (Appendix A) presented relevant objective facts regarding (1) the actual observed outcomes most relevant for the technologies at issue (trends in market penetration of flame-retention-head oil burners and average energy efficiency of residential refrigerators, heat pumps, and central air conditioners) and (2) the factors that are most likely to have contributed to those outcomes.

2. We asked respondents to react to the information presented: Is it complete? Are there important factors missing that they would want to add?

3. We then asked respondents to describe (in qualitative terms) how the actual observed outcomes would be different without BTO R&D.

4. Finally, we asked respondents to quantify how observed outcomes or trends would have been different without BTO R&D (i.e., we asked them to characterize counterfactual trends in quantitative terms), so that the difference between actual and counterfactual trends could be interpreted as the impact attributable to BTO R&D. The exact approach to quantitative data collection was different for each of the three technologies and is therefore discussed separately in the respective technologies' sections.

2.1.3 Disentangling Impacts: R&D and Standards

R&D and energy performance standards are complementary. BTO R&D would not have been as impactful had the standards programs not existed. However, the purpose of this evaluation was not to quantify the impact of the standards program but rather to isolate, to the extent practicable, the impacts attributable to BTO R&D.

Special attention was paid in interviews to the treatment of energy performance standards. Because BTO R&D could have affected the timing and levels of new standards, it would not necessarily be appropriate to hold those factors constant. Experts were therefore asked to hold constant the framework within which standards are developed and promulgated and characterize counterfactual trends without BTO R&D. If the absence of BTO R&D would, in the expert's opinion, have had an effect on the timing or levels of standards, then that would be reflected in her response. In this way, the impact of the standards program is to some extent excluded and the impact of the R&D is isolated.

To be sure, the R&D program and the standards program are complementary; on this point experts were unanimous, although the nature of this complementarity was different for refrigeration versus space heating and cooling.[9] Therefore, the benefits attributed to BTO R&D are partly due to the standards program, in the sense that BTO R&D would not have been as impactful had the standards programs not existed. However, the purpose of this evaluation was not to quantify the impact of the standards program. Rather, our remit was to isolate, to the extent practicable, the impacts attributable to BTO R&D.

Qualitative Differences between Energy Performance Standards and the Montreal Protocol

Whereas energy performance standards for appliances and heating and air-conditioning equipment are the purview of DOE and may be influenced at least indirectly by BTO R&D, international treaties like the Montreal Protocol are more removed, and exogenous to the interactions between DOE and industry related to energy performance standards.[10]

The Montreal Protocol on substances that deplete the ozone layer was agreed upon in 1987 and then revised eight times during the 1990s to accelerate its phase-in and increase its stringency. BTO's R&D in alterative refrigerants, together with R&D efforts at EPA and NIST, played an important role in industry being able to cost effectively meet these requirements for air conditioners and heat pumps. An evaluation of alternative refrigerants research performed by NIST, partly funded by DOE, estimated a benefits-to-cost ratio of 4-to-1, considering only R&D cost reductions realized by the private

[9] For refrigerators, and appliances more generally, energy performance is not a key selling point for most consumers, who tend to be more interested in other features. Standards programs are therefore essential to influence companies to direct R&D toward energy performance. In contrast, manufacturers of heat pumps and central air conditioners do differentiate their product lines by energy performance, the highest-priced (highest profit margin) product lines being the most energy efficient. There, the effect of standards is to push manufacturers to incorporate the energy-efficient components and designs into lower-priced (lower profit margin), larger-market product lines sooner than they otherwise would. On the interplay between standards and R&D more generally, see Newell, Jaffe, and Stavins (1999), Porter and Van der Linde (1995), and Popp, Newell, and Jaffe (2010).

[10] DOE is tasked with establishing energy conservation and efficiency standards under several pieces of legislation beginning with the Energy Policy and Conservation Act (EPCA) of 1979. The National Appliance Energy Conservation Act of 1987 directed the DOE to develop efficiency standards for consumer appliances and set out a schedule for updating them periodically. In 1992, the Energy Policy Act (EPAct) added standards for more appliances. For more details, see https://energy.gov/eere/buildings/history-and-impacts.

sector among the benefits (Shedlick, Link, and Scott, 1998). BTO R&D investments continue to fund alternative refrigerants research (Abdelaziz et al., 2015, 2016).

During the interviews, experts were asked if BTO research had any impact on the timing or stringency of the Protocol's revisions during the 1990s. The consensus was that, whereas BTO R&D helped industry in complying with the Protocol, it had no impact on the timing or stringency of the Protocol itself. Respondents indicated that the Montreal Protocol was an international effort to phase out CFCs and other ozone depleting substances and was driven almost exclusively by environmental concerns.

In contrast, DOE is directly responsible for establishing energy performance standards. In 1992 and 2006, Minimum Energy Performance Standards (MEPS) were put in place raising the minimum performance of air conditioners and heat pumps to 10 SEER (from 8 SEER) and to 13 SEER (from 10 SEER) respectively.[11] U.S. energy performance standards for residential refrigerators took effect in 1990, 1993, 2001, and 2014. Asked if BTO R&D had influenced either the timing or levels of energy performance standards, most experts credited BTO R&D with at least one of these types of effects. These results are discussed in greater detail in Sections 4 and 5.

2.1.4 Estimation of Benefits Relative to the Next Best Technology Alternative

In this type of benefit-cost evaluation, the counterfactual situation is often defined in terms of the next best technology alternative. The question to consider is: In the absence BTO's R&D contributions under study, how would the development and adoption of new technologies have unfolded?

Flame-retention-head oil burner

In the case of the flame-retention-head oil burner, the next best available technology is assumed to be the incumbent non-flame-retention burners. But we go further than defining the counterfactual as a non-flame-retention burner in place of each

[11] Heat pumps and central air conditioners are rated according to their seasonal energy efficiency ratio (SEER), which indicates the relative amount of energy needed to provide a specific heating or cooling output. Specifically, SEER is the ratio of heating or cooling output to the amount of energy consumed. Thus, a higher SEER represents greater energy-efficiency.

flame-retention burner. Flame-retention burners were available and had a very small presence in the market before DOE became involved. We characterize DOE's contribution not as the replacement of one technology with another, but rather as the accelerated market acceptance, and hence the accelerated diffusion of the flame-retention-type oil burners.

This choice foregoes estimation of a portion of the BTO impact. Experts involved in the flame-retention-head burner program described a highly collaborative, iterative process involving BTO (specifically Brookhaven National Laboratory), oil burner manufacturers, and furnace and boiler manufacturers. Manufacturers provided equipment to Brookhaven National Laboratory for successive rounds of testing. After each round, everyone learned from the results and used this information to improve designs for greater energy efficiency. The publication of these test results by a universally trusted third party drove a highly risk-averse industry to adopt the new technology in place of the old. This is the effect we quantify. Some interviewees suggested that the program also contributed to improvements in the new technology—by testing early designs of multiple manufacturers and providing feedback manufacturers used to improve designs for subsequent rounds of testing, and iterating this process—but we did not think we had sufficient information to attempt to quantify this effect.

Advanced Refrigeration, Heat Pump Design Model and Alternative Refrigerants Research

For residential refrigerators, heat pumps, and central air conditioners, the characterization of the next best technology alternative is more nuanced. These products consist not of a single technology but rather complex systems of technologies: compressor, motor, controls, heat exchangers, refrigerant fluids and lubricants, and (in the case of refrigerators) insulation.[12]

Rarely if ever does such a technology emerge from a national laboratory in its final commercial form. Research at a national laboratory might inform companies' efforts to develop a new technology, as when high-quality refrigerant properties data

[12] In the R&D, innovation, and technological change literature focusing on intellectual property rights, a distinction is made between discrete product industries—like chemicals—and complex product industries—like appliances, heat pumps, central air conditioners—comprised of a large number of patentable elements. See Cohen et al. (2000).

generated by a national lab enables a company to design vapor-compression equipment to use a new refrigerant. Or a prototype of a component, like a heat pump compressor, might emerge from a national lab, in need of further development by a component manufacturer and testing by an OEM before it can be integrated into a commercial product.

Moreover, multiple technologies—both component and systems technologies, characterized by different consumer prices, producer costs, and energy efficiency levels—coexist in the market at any given time.

In this setting, it is not appropriate to think of a "BTO technology" and a next best alternative "non-BTO technology". Rather, BTO R&D enabled or contributed in various ways to private companies' efforts to develop and commercialize more energy-efficient products. We therefore conceptualize the next-best-alternative technology as the average energy efficiency of products shipped in a given year that would have been observed without the BTO R&D contributions.

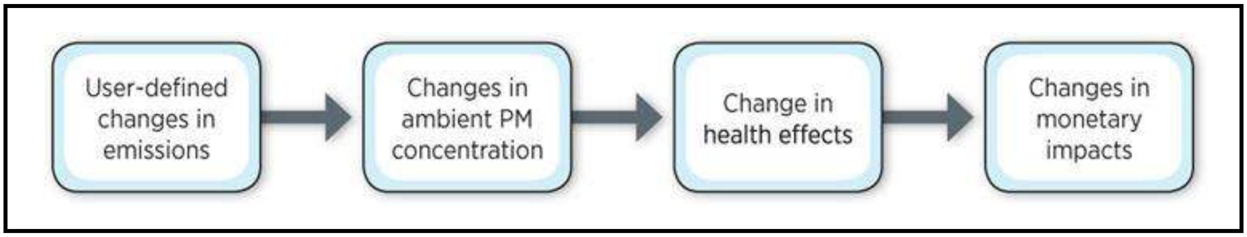
2.2 APPROACH TO ENVIRONMENTAL HEALTH BENEFITS ESTIMATION

Environmental benefits associated with BTO's R&D investments were quantified on the basis of energy savings. Emissions reductions were quantified by applying emissions factors to energy savings estimates. These emissions reductions were then fed into the Co-Benefits Risk Assessment (COBRA) model, which was developed by the U.S. EPA to enable users to obtain first-order approximations of benefits due to different air pollution mitigation policies. The COBRA model provides estimates of health effect impacts and the economic value of these impacts resulting from changes in the physical units of emitted pollutants. An overview of the COBRA model and how it works is available from U.S. EPA (2014, 2015). A brief overview of the COBRA model is provided here.

Overview of the COBRA Model

At the core of the COBRA model is a source-receptor (S-R) matrix that translates changes in emissions to changes in 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 2-1 provides an overview of the modeling steps.

Figure 2-1. COBRA Model Overview



Source: U.S. EPA (2014).

Changes in Emissions→ Changes in Ambient PM Concentrations

The user provides changes (decreases) in emissions of pollutants ($PM_{2.5}$, SO_2, NO_x, VOCs, NH_3) and identifies the economic sector from which the emissions are being reduced. For this analysis, the impacted sectors were Residential Distillate Oil Combustion (flame-retention-head oil burner impacts) and Electric Utility Fuel Combustion (advanced refrigeration and heat pump design model and alternative refrigerants research impacts). These changes are in total short 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.[13]

The S-R matrix consists of fixed transfer coefficients that reflect the relationship between annual average PM concentration values at a single receptor in each county (a hypothetical monitor located at the county centroid) and the contribution by PM species to this concentration from each emission source. This matrix provides quick but rough estimates of the impact of emission changes on ambient PM levels as compared with the detailed estimates provided by more sophisticated air quality models (U.S. EPA, 2015).

[13] 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 was used to determine the emission location as input to the S-R matrix.

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 U.S. EPA analyses, the health impact functions and the unit economic value used in COBRA are the same as the ones used for the Mercury and Air Toxics Standards (MATS) Final Rule.

The model provides changes in the number of cases for each health effect between the baseline emissions scenario (included in the model) and the analysis scenario (input by the user). The different health endpoints are summarized in Table 2-3 and described briefly below. For additional detail on the epidemiological studies, functional forms, and coefficients used in COBRA, see Appendix C of the COBRA user's manual (U.S. EPA, 2015).

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 Krewski et al. (2009) and by a Six-City cohort by Laden et al. (2006). These two studies provide a high and low estimate of mortality associated with changes in ambient PM2.5. COBRA includes different mortality risk estimates for both adults and infants. Infant mortality is based on Woodruff et al. (1997). Because of the high monetary value associated with prolonging life, mortality risk reduction is consistently the largest health endpoint valued in the study.

Nonfatal heart attacks were linked by Peters et al. (2001) to PM exposure. Nonfatal heart attacks were modeled separately from hospital admissions because of their lasting impact on long-term health care costs and earning. COBRA provides a high and low estimate of incidence for nonfatal heart attacks based on differing literature.

Table 2-3. Health Endpoints Included in COBRA

Health Effect	Description
Mortality	Number of deaths (adult or infant)
Acute bronchitis	Cases of acute bronchitis
Nonfatal heart attacks	Number of nonfatal heart attacks
Respiratory hospital admissions	Number of cardiopulmonary-, asthma-, or pneumonia-related hospitalizations
CDV-related hospital admissions	Number of cardiovascular-related hospitalizations
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
MRAD	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 loss days	Number of work days lost due to illness
Asthma exacerbations	Number of episodes with cough, shortness of breath, wheeze, and upper respiratory symptoms in asthmatic children

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, CO, and ozone; Moolgavkar (2000, 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. Sheppard (2003) 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. Because 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. However, the findings showed some variability across years.

Asthma exacerbations estimates were pooled from Ostro et al. (2001) and Mar et al. (2004) to calculate impacts of changes in air quality on asthmatic children. Cough, wheeze, and shortness of breath are all considered to be exacerbations.

Changes in Health Effects → 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 Appendix F of the COBRA user’s manual (U.S. EPA, 2012d). Estimation of the monetary unit values varies by the type of health effect. For example, reductions in the risk of premature mortality are monetized using value of statistical life estimates. Other endpoints such as hospital admissions use cost of illness units that include the hospital costs and lost wages of the individual but do not capture the social (personal) value of pain and suffering. COBRA allows users to choose between a discount rate of 3% or 7% to calculate the present value of health effects that may occur beyond the year 2017.

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.

2.3 APPROACH TO ENERGY SECURITY BENEFITS ESTIMATION

Energy security benefits are measured in terms of the reduction of our nation’s dependency on imported crude oil. Savings of heating oil associated with flame-retention-head burners and electricity savings associated with improvements in the efficiency of residential refrigerators, heat pumps, and central air conditioners are converted to avoided barrels of imported crude oil over the time period of the analysis. Following EERE’s evaluation guidelines (Ruegg, O’Connor, and Loomis, 2014), no additional monetary value is assigned to energy security impacts, and so these impacts are not considered in the calculation of economic impact metrics (net present value, benefit-to-cost ratio, and internal rate of return).

Following Ruegg, O’Connor, and Loomis (2014), avoided imported crude oil in a given year is calculated by multiplying avoided U.S. crude oil consumption by the fraction of crude oil imported in that year:

$$Avoided\ Imports = (Avoided\ Consumption) \times \left(\frac{Imported\ Crude}{Total\ Crude\ Supplied}\right)$$

This formula is operationalized as follows, using data on the supply and disposition of crude oil in the United States, downloaded from the U.S. Energy Information Administration (EIA, 2017b). For 1981 onward, the ratio of imported crude to total crude supplied is calculated by dividing U.S. Imports of Crude Oil by U.S. Refinery and Blender Net Input of Crude Oil. For the years 1971 through 1980, for which U.S. Refinery and Blender Net Input of Crude Oil is unavailable, the calculation is based on a different ratio of U.S. Imports of Crude Oil to an alternative denominator:

$$\begin{pmatrix} U.S.Field \\ Production \\ of\ Crude\ Oil \end{pmatrix} + \begin{pmatrix} U.S.Supply \\ Adjustment \\ of\ Crude\ Oil \end{pmatrix} + \begin{pmatrix} U.S. \\ Imports \\ of\ Crude\ Oil \end{pmatrix} - \begin{pmatrix} U.S. \\ Exports \\ of\ Crude\ Oil \end{pmatrix}$$

For 1981 onward, when it is possible to calculate both ratios, their correlation is essentially perfect (correlation coefficient of 0.9997). For those years, the simple ratio of imports to refinery inputs is given by adding 0.007 to 0.99 times the alternative ratio (based on a simple linear regression of the simple ratio on the alternative). Table 2-4 gives the percentages of imported crude for 1977 through 2015.

Table 2-4. Percentage of U.S. Crude Oil Supply Imported.

Year	Percentage	Year	Percentage	Year	Percentage
1977	44.9%	1990	44.0%	2003	63.2%
1978	42.9%	1991	43.5%	2004	65.2%
1979	44.2%	1992	45.4%	2005	66.5%
1980	39.1%	1993	49.9%	2006	66.4%
1981	35.3%	1994	50.9%	2007	66.2%
1982	29.6%	1995	51.7%	2008	66.8%
1983	28.5%	1996	52.9%	2009	62.9%
1984	28.4%	1997	56.1%	2010	62.6%
1985	26.7%	1998	58.5%	2011	60.3%
1986	32.9%	1999	59.0%	2012	56.8%
1987	36.4%	2000	60.2%	2013	50.5%
1988	38.6%	2001	61.7%	2014	46.3%
1989	43.6%	2002	61.2%	2015	45.5%

Source: Calculated based on EIA (2017b).

The following sections explain how avoided consumption of crude oil is calculated from avoided consumption of heating oil (for the flame-retention-head oil burner) and avoided electricity consumption (for residential refrigerators, heat pumps, and central air conditioners).

2.3.1 Calculating Avoided Crude Oil Consumption: Flame-Retention-Head Oil Burner

A 42-gallon (U.S.) barrel of crude oil yields about 45 gallons of petroleum products because of refinery processing gain. Therefore, we assume that 45 gallons of heating oil saved equates to one barrel of crude oil saved.

This is an appropriate assumption notwithstanding the small fraction of refinery output that is heating oil.[14] The relative composition of refinery output is not fixed. As demand for heating oil falls, relative to the demand for other products (e.g., gasoline, jet fuel, and ultra-low-sulfur distillates), so does its share of refinery output. Therefore, assuming that refinery gain for heating oil specifically is roughly the average 7% for all refinery output, refinery demand for crude will fall by 1 barrel for every 45 gallons of heating oil taken away from total refinery output.

2.3.2 Calculating Avoided Crude Oil Consumption: Residential Refrigerators, Heat Pumps, and Central Air Conditioners

Crude oil saved by improvements in the energy efficiency of residential refrigerators, heat pumps, and central air conditioners is calculated in two steps. First, electricity savings are converted into savings of petroleum liquids. Then, we again adjust for refinery processing gain by multiplying barrels of petroleum liquid saved by 42/45 to obtain saved barrels of crude.

Savings of petroleum liquids in a given year are calculated by multiplying the number of barrels of petroleum consumed for electric utility generation by the ratio of DOE-attributed electricity savings to total U.S. electric utility generation.

[14] In 2016, heating oil (included in "other distillates") accounted for less than 1% of refinery output (EIA, 2017a).

2.4 APPROACH TO KNOWLEDGE BENEFITS ANALYSIS

The intent of knowledge benefits analysis is to determine the impact of BTO R&D on subsequent developments both within and outside the areas of HVAC, appliances and water heating technologies, thereby capturing both direct and spillover knowledge impacts.

In addition to energy and other resource impacts, environmental impacts, and energy security impacts, a fourth category of impacts treated by this evaluation is Knowledge Benefits. The nature of R&D is that it generates new knowledge, thereby adding to the knowledge base from which additional invention and innovation draw. This chapter assesses selected knowledge benefits resulting from BTO's funding of R&D in HVAC, Appliances, and Water Heating technologies by examining patents and patent citations. Advanced refrigeration is covered by appliance patents. Heat pump design model and alternative refrigerants research, given our focus for this technology area on heat pumps and central air conditioners, is covered by HVAC. The patent analysis also covered a fourth technology area, which was not included in the quantitative analysis but which is a promising area for future impact analysis: water heating technology and especially heat pump water heaters.

2.4.1 Background

Knowledge Outputs of BTO related to its funding of HVAC, Appliances, and Water Heating encompass both explicit knowledge outputs such as knowledge embedded in patents, publications, presentations, models, prototypes, technology demonstrations, databases, and research tools, as well as tacit knowledge outputs such as the knowledge embodied in trained and experienced people, amplified by the formation of networks of skilled people and institutions.

Though all of these knowledge outputs are potentially important to generating direct and spillover benefits from BTO's R&D program, patents and citations of patents are considered particularly effective indicators of innovation. Past studies have shown a strong positive relationship between the frequency of patent citations and the technological importance and commercial value of the patents. Further, patents have the advantage of being measurable quantitatively and their dissemination traceable using objectively derived data.

2.4.2 Scope and Goals

Due to budgets constraints on the scope of this evaluation, priority has been given in this assessment to the identification and analysis of patents and publications cited by patents—explicit knowledge outputs attributed to BTO funding in the designated technology areas.

This analysis of knowledge benefits—with its focus on patents and publications cited by patents—serves three goals:

- To measure the extent of the dissemination of BTO-funded knowledge benefits within the three areas of technology focus—HVAC, appliances, and water heating—and knowledge spillovers to other technology areas.
- To assess the comparative influence of BTO-funded knowledge benefits on downstream innovations by the leading innovators in each of the three technology areas.
- To provide supporting information that complements the quantitative assessment of impacts attributable to BTO R&D.

2.4.3 Methods Overview

The intent of this analysis is to determine the impact of BTO R&D on subsequent developments both within and outside the areas of HVAC, Appliances and Water Heating technologies, thereby capturing both direct and spillover knowledge impacts. The processes employed require the construction of data sets, followed by forward and backward tracing using citation analysis.

The ***forward tracing*** starts with the BTO-attributed[15] set of patents in each technology and looks for where they lead in terms of influence. The ***backward tracing*** starts with the set of relevant patents owned by the leading innovative companies in each technology area, and compares the influence of the BTO-attributed patent set with the companies' patent sets.

[15] The term "BTO-attributed" is used to indicated patents that resulted largely from BTO funding of R&D, whether the R&D was carried out by DOE, DOE-sponsored laboratories, universities, private companies, or other organizations funded by DOE/BTO. All of these patents are not assigned to DOE; it is unlikely that DOE paid for patent-filing costs; and DOE often has not have paid 100% of the R&D that led to the patented invention. Using the approach described in detail in Appendix B, a set of patents were identified as BTO-attributed. Note that short-hand designations are sometimes used in the text for BTO-attributed, such as "the BTO set", or, for the three technology areas, "BTO-HVAC patent families", "BTO-Appliances patent families", and "BTO-Hot Water patent families".

At the individual patent level, the analysis identifies those BTO patents that have been particularly influential. Citations Indexes are used to highlight these patents.

Patents include those filed with the U.S. Patent Office (USPO), the European Patent Office (EP), and the World Intellectual Property Organization (WO), and are assembled using several search mechanisms. The BTO set was verified with BTO staff as attributable to, or highly likely attributed to, BTO-funded R&D. The set of patents of the leading innovative companies in each technology area are found by identifying the companies in each area that have the largest number of relevant patents assigned to them and listing the patents in the portfolio of each company. Then patents assigned to BTO and those assigned to the companies are grouped into patent families, where a patent family contains all of the patents and patent applications that result from the same original patent application (named the 'priority application'). For more details on the construction of the patent sets for the analyses, see Appendix B.

Citation analysis is the tool used for tracing the influence of the identified patents and publications. It relies on the fact that the front page of a patent document contains a list of references—including earlier patents, scientific papers, and various other types of documents such as technical reports—that establish "prior art", that is, the state of the art at the time of the patent application. Patent citation analysis focuses on the links between generations of patents that are made by these prior art references. The approach is based on the idea that earlier patents and other documents cited by later patents help form the technological basis of the later patents, and, further, that the more highly cited these earlier patents and other documents are, the more important they likely have been to subsequent innovation. Thus, patent citations analysis has been used extensively to trace the influence of research on technological developments over time.

2.5 MEASURES OF SOCIAL ECONOMIC RETURN

Zvi Griliches (1958) and Edwin Mansfield et al. (1977) pioneered the application of fundamental economic insight to the development of estimates of private and social rates of return to public and private investments in R&D. Streams of investment outlays through time—the costs—generate streams

The reliance of this study on in-depth interviews with experts in industry and other relevant sectors is very much in the tradition and spirit of Edwin Mansfield, who pioneered this type of research and thereby made immense contributions to the economics of R&D, innovation, and technological change.

of economic surplus through time—the benefits. Once identified and measured, these streams of costs and benefits are used to calculate rates of return, benefit-to-cost ratios, and other performance measures. Such analysis can answer the evaluation question: What is the social rate of return to the program's investments? And more simply: Has the program overall been worthwhile?

This evaluation builds on the Griliches/Mansfield model in terms of comparing, in a systematic way, public benefits of BTO's R&D investments with the costs of those investments (see Link and Scott, 2010). Our reliance on in-depth interviews with experts in industry and other relevant sectors is very much in the tradition and spirit of Edwin Mansfield, who pioneered this type of research and thereby made immense contributions to the economics of R&D, innovation, and technological change.[16]

Three investment performance measures are calculated:

- net present value (NPV),
- benefit-to-cost ratio (BCR), and
- internal rate of return (IRR).

NPV, according to Circular A-94 of the Office of Management and Budget (OMB) (OMB, 1992, p. 3), is a standard evaluation criterion for deciding whether a government program can be justified on economic principles—the discounted monetized value of expected net benefits (i.e., benefits minus costs). NPV is computed by assigning monetary values to benefits and costs, discounting future benefits and costs using an appropriate discount rate, and subtracting the sum total of discounted costs from the sum total of discounted benefits. Discounting benefits and costs transforms gains and losses occurring in different time periods to a common unit of measurement. Generally, projects with positive NPV should be undertaken and those with negative NPV should not. Among those projects with positive NPVs, the larger the value of NPV the greater the net benefits to society.

For this analysis, benefits and costs are discounted to the beginning of 1976. Benefits are discounted as if they accrued at the end of each year. Costs are discounted as if they accrued at the beginning of each year. For example, total monetary benefits accruing in 1976 would be discounted by one year,

[16] See Link and Scherer (2005).

benefits accruing in 1977 would be discounted by two years, and so on. Investment costs incurred in 1976 are not discounted, costs incurred in 1977 are discounted one year, and so on. Thus, NPV is calculated as $PVB - PVC$, where PVB and PVC are the present-valued (i.e., 1976-valued) benefits and costs, calculated as follows:

$$PVB = \sum_{y=1976}^{2015} B_y(1+r)^{1976-y-1}$$

$$PVC = \sum_{y=1976}^{2015} C_y(1+r)^{1976-y}$$

In these formulas, B_y represents the real-valued benefits in year y, C_y represents the real-valued costs in year y, and r is the discount rate. Note the extra year by which benefits are discounted. By real-valued, we mean that nominal dollars are converted to the constant dollars of a reference year, in this case 2015. This is done using an inflation index, in this case the consumer price index (CPI).

BCR is the ratio of the present value of benefits to the present value of costs. A BCR greater than 1 indicates that the present value of quantified benefits outweighs the present value of calculated costs. The larger the value of a BCR, the greater the net benefits to society. Using the formulas given above, BCR is calculated as the ratio of PVB to PVC.

IRR is the discount rate that sets NPV equal to zero, or it is the discount rate that would result in a BCR equaling 1. The IRR's value can be compared with conventional rates of return for comparable or alternative investments. An IRR value greater than the return on an alternative investment (generally measured as equal to the discount rate) is interpreted to mean that the project was, in a comparative sense, socially valuable. By thinking of the formulas given above as functions of the discount rate, $PVB(r)$ and $PVC(r)$, the IRR is found by numerical methods. It is the value of r for which $PVB(r) = PVC(r)$.

Fundamental to the calculation of NPV and a BCR is the discount rate used to reference all values to the initial time period in which investment costs began. Following OMB (1992) guidelines, a 7% real (i.e., adjusted for inflation) rate of discount was used. The use of a real discount rate means that

Benefits attributable to BTO's R&D investments in selected technology areas are compared to investment costs for the entire HVAC, water heating, and appliance R&D portfolio, yielding conservative estimates of the overall performance of the portfolio.

all measured benefits and all investment costs are first converted into real, constant dollars to account for inflation, before they are discounted. According to OMB (1992, p. 8): "Constant-dollar benefit-cost analyses of proposed investments and regulations should report net present value and other outcomes determined using a real discount rate of 7 percent."

For comparative purposes, and following the more recent suggestion in OMB Circular A-4 (OMB, 2003), a 3% real rate of discount was also used in the NPV and BCR calculations in Sections 7 and 8.[17]

2.6 TECHNOLOGY SELECTION FOR PORTFOLIO APPROACH

As alluded to in the introduction, this study employs a portfolio approach as a cost-effective alternative to evaluating individual R&D projects. By focusing the quantitative analysis on a few technology areas within BTO's larger R&D portfolio, the analysis supports conclusions about the entire portfolio. The appropriateness of focusing on only a few projects relies on the fact that a relatively small share of projects in high-risk R&D portfolios typically account for most of the benefits. Projects destined for success cannot be identified at the time they are funded, and so a successful portfolio is one in which the rates of return on successes are large enough to cover the cost of projects that do not achieve technical or commercial success,

[17] For federal economic evaluations, OMB issues directives on discounting and discount rates for different types of evaluations. Circular A-94 (OMB, 1992) directs the use of a 7% real discount rate for federal benefit-cost analysis. More recent guidance is provided by Circular A-4 (OMB, 2003), which pertains to benefit-cost analysis used as a tool for regulatory analysis. It notes that Circular A-94 stated that a real discount rate of 7% should be used in benefit-cost analysis as an estimate of the average before-tax rate of return to private capital in the U.S. economy. This rate is an approximation of the opportunity cost of capital. Circular A-4 further notes that OMB found in a subsequent analysis that the average rate of return to capital remained near 7%. It also points out that Circular A-94 recommends using other discount rates to show the sensitivity of the estimates to the discount rate assumption and notes that the average real rate of return on long-term government debt has averaged about 3%. Circular A-4 requires the use of both a 7% and a 3% real discount rate for a benefit-cost analysis conducted for regulatory purposes. When regulation primarily and directly affects private consumption (e.g., through higher consumer prices for goods and services), a lower discount rate is appropriate, and OMB suggests a 3% real rate of time preference. For the purpose of discounting constant dollar cash flows in this study, both rates are used—a 7% and a 3% real discount rate—even though the purpose is not regulatory.

Benefits are quantified for three technology areas within BTO's HVAC, water heating, and appliance R&D portfolio:

1. Flame-retention-head oil burners

2. Advanced refrigeration technology

3. Heat pump design model and alternative refrigerants research

endemic features high-risk R&D portfolios. A retrospective evaluation like this one can therefore select projects that are generally recognized to have been successful, quantify their benefits, and compare these benefits to the investment cost of the entire portfolio.

This analysis compares the entirety of BTO's HVAC, water heating, and appliances R&D portfolio costs, from 1976 through 2015, against the benefits, attributable to those BTO investments, in three technology areas:[18]

1. **flame-retention-head oil burners**, efforts known as Project Oilheat, in which BTO conducted technical research (testing fuel savings and verifying safety and reliability of retrofits) and market conditioning activities (disseminating test results, partnering with states' energy offices and oil dealer trade associations in communications campaigns and technician training), from 1979 to 1981;

2. **advanced refrigeration**, focusing on BTO's research related to the energy-efficiency of residential refrigerators;

3. **heat pump design model and alternative refrigerants research**, including BTO's R&D related to the energy-efficiency of heat pump and air conditioning technology.

These three technology areas were selected from BTO's HVAC, water heating, and appliances R&D portfolio, which was the focus of this study and which is one of four long-standing R&D portfolios within BTO's Emerging Technologies Program. The other three portfolios in the Emerging Technologies Program address the technology areas of 1) lighting, 2) windows and building envelope, and 3) building energy modeling.[19] In addition to the three technology areas selected for this evaluation, the HVAC, water heating, and appliance portfolio has included such other technology areas as thermally activated heat pumps, combustion and thermal distribution, and household appliances like dishwashers and clothes washers and dryers.

[18] DOE was established on October 1, 1977. The analysis includes investments in building technologies made by DOE's predecessor agencies in 1976 and the beginning of 1977.

[19] More recently, BTO has added R&D portfolios addressing sensors and controls and transactive energy.

In addition to the three technologies selected, heat pump water heating technology was initially considered for inclusion in the quantitative impact analysis and later dropped, because the technology's relatively recent introduction to the market made it so that its strictly retrospective impacts were significantly lower than those of the three selected technology areas. BTO contributions to heat pump water heating technology are described in Section 6, together with a knowledge impacts analysis.

2.6.1 Technologies Considered for Inclusion but not Selected

The following technologies were considered for inclusion but not selected.

Condensing Furnace and Boiler Materials

Condensing furnace models (having annual fuel utilization efficiency [AFUE] of at least 90%) have commanded an increasing share of the nonweatherized gas furnace market since the early 1980s, increasing from less than 10% to around 50%. In northern states, the market share of condensing models has risen from 12% to more than 65%. This change has contributed to shipments-weighted average AFUE of nonweatherized gas furnaces from under 70% to more than 85%, a trend that represents significant energy savings. That condensing gas furnaces have any market presence at all may be largely attributable to DOE research. At the very least, the diffusion of gas condensing furnaces would have been delayed by some years had DOE not been able to quickly offer a solution to corrosion problems with early models.

Beginning in 1979, DOE collaborated with the Gas Research Institute (GRI) to develop materials and furnace design techniques for condensing gas furnaces. DOE awarded four contracts through Brookhaven National Laboratory (BNL) and four through GRI. The work was performed in collaboration with the Canadian Gas Research Institute. Early work indicated that common stainless steels were adequate for gas condensing furnaces. DOE continued to research materials that could withstand the more corrosive environment of oil condensing furnaces and was therefore able to respond quickly when gas furnaces installed in homes experienced significant corrosion problems. (The corrosion was caused by a chloride ion mechanism; household cleaning products containing chlorine were discovered to cause the corrosion.) The stainless steel alloys DOE had been investigating for use in oil furnaces proved to be the answer for gas condensing furnaces.

Gas Condensing Water Heating

From 1999 to 2004, DOE, through NETL, funded A.D. Little/TIAX to develop a residential condensing gas water heater. The Vertex was first commercialized in the second quarter of 2006 by A.O. Smith. The design innovation in the product is a helical heat exchanger, which increases heat exchange by causing the exhaust gases to swirl and circulate. The first commercialized model achieved 90% thermal efficiency. Compared with a conventional, noncondensing gas-fired water heater with 78% to 80% efficiency, the first model reduces energy consumption by about 30%. Additionally, the glass-lined carbon steel heat exchanger, in place of stainless alloy, made manufacture simpler and less costly.

A second model, the Vertex 100, with 96% efficiency, was commercialized in the second quarter of 2008. The heat exchanger technology has also been used in the Cyclone XHE line of commercial water heaters, commercialized in 2007. Cyclone BTH-300 and BTH-400 models achieve 99% efficiency.

Gas Commercial Rooftop Heat Pump

The result of an R&D collaboration between ORNL and IntelliChoice, the NextAire Packaged Gas Heat Pump achieves the following advantages over electric rooftop heat pumps:

- Avoids the energy losses inherent in electrical energy generation, transmission, and conversion to mechanical energy by the heat pump motor.
- Reduces peak demand for electrical power for heating and air conditioning.
- By smoothing seasonal fluctuations in demand for natural gas, enables gas utilities to reduce costs by buying gas at annual instead of spot prices.

DOE made the following important contributions to the development of the NextAire, as expressed by industry experts familiar with its devleopment:

- For every product in every level of development at the IntelliChoice Las Vegas R&D center, there was a “sister unit” at ORNL.

- The psychrometric test chamber at ORNL was critical to development but was beyond IntelliChoice's capacity to reproduce independent of ORNL.
- ORNL personnel brought "priceless" experience and expertise to the table, especially for the development of many components and design elements such as the angle at which a coil sits, the type of coil, the material in the coil, the type of refrigerant, the number of fans for optimal airflow; electronics, and software development (algorithms and software).
- The complementary expertise of chemical engineers at ORNL was especially helpful (to complement the expertise of mechanical engineers—thermodynamic engineers—at IntelliChoice).

NextAire was first commercialized in a limited way in 2004, through field tests on military bases. All these units are still going strong. The NextAire was commercialized for public consumption in 2009 and 2010.

Ground-Coupled Integrated Heat Pump

The major advance of this technology is the integration of year-round, on-demand water heating into a heat pump space conditioning system. (A family of four spends $500 to $600 per year for water heating, and the ClimateMaster Trilogy 45 can cut that in half, conservatively). In addition, with a variable speed compressor, the Trilogy has a cooling energy efficiency ratio of 45—greater than that of the Waterfurnace 7 Series (at 41, also with a variable speed compressor) or the best 2-speed compressor ground-coupled heat pumps (at 30).

The Trilogy was available in a limited release from 2012 to 2014; its full launch occurred in March 2014.

An even larger impact, still in part attributable to BTO, may come from efficiency gains in other ClimateMaster products. Many components looked at for the Trilogy were rolled into mature products well before the Trilogy was commercialized. One example was a variable-speed electronically commutated motor (ECM) driven pump, 50% more efficient than the next best alternative—still more efficiency is generated when tweaks are made on the control side to optimize for the new ECM-driven pumps.

Aerosol Duct Sealing and Research to Support ASHRAE Standard 152

DOE funded early R&D on the Aeroseal aerosol duct sealing technology, which is a more durable and cost-effective approach to duct sealing than the manual application of mastic (which is often impractical post-construction when the duct work is all but inaccessible).

The impacts go beyond the number of Aeroseal-treated homes and commercial buildings. The availability of the technology and ASHRAE Standard 152 (sealing test method for determining the seasonal efficiency of residential distribution systems, including forced air, hydronic, etc., developed by DOE researchers at BNL and LBNL) has given some impetus to states (California, certainly, Florida, and also others) to tighten building codes.

3 Flame-Retention-Head Oil Burner

This section describes BTO R&D related to flame-retention-head oil burner technology and presents estimates of benefits attributable to this R&D. Our approach to impact estimation for this technology differs in important ways from our approach to the other two technology areas. Whereas impact estimates for advanced refrigeration and heat pump design model and alternative refrigerants were based on formal interviews using interview guides approved by the Office of Management and Budget (OMB) pursuant to the Paperwork Reduction Act, impact estimates for the flame-retention-head oil burner were based on preliminary scoping interviews with eight experts and a subsequent follow-up with these experts in which we shared a summary of our analysis and elicited further comments. In contrast, we conducted 44 formal interviews for advanced refrigeration and 39 for heat pump design model and alternative refrigerants.

Despite the small number of experts with whom we spoke, because of their depth of knowledge and the novelty of our approach to impact estimation, we believe we have made a useful contribution in the context of earlier attempts to quantify the impact of this technology, which we summarize at the end of Section 3.5.

3.1 TECHNOLOGY OVERVIEW

BTO conducted technical research (testing fuel savings and verifying safety and reliability of retrofits) on flame-retention-head oil burners as part of a broader combustion research program from 1977 to 1979. BTO also conducted market conditioning activities (disseminating test results, partnering with states' energy offices and oil dealer trade associations in communications campaigns and technician training) through the Fuel Oil Marketing and Demonstration Program from 1979 to 1981. These activities have also been referred to as ***Project Oilheat***, which comprises three related programs:

- 1977-1979. **Combustion Research Program and Oil Heat R&D Program**. Brookhaven National Laboratory (BNL) evaluated alternative energy-saving technologies in the lab and selected FRHOB for additional testing in the field. Tests demonstrated fuel savings ranging from 5% to 22%, and a payback period for a refit FRHOB of one to three years.[20]

- 1978-1981. **Fuel Oil Conservation Marketing and Demonstration Program (FOCM)**. BTO, through BNL, partnered with 10 states (state energy offices, dealer associations, dealers) in dissemination of test findings, marketing campaigns, and technician training. NY and MA received grants for 1978-1979 heating season. CT, NH, NJ, WI, and PA received grants in 1979. RI, ME, and NC received grants in 1980.

- 1979-1981. **Oil Refit Program and Oil Refit Option Qualification Field Test Program**. BNL provided technical support to the FOCM pilot program which tested Long Island, NY homeowners' heating units for efficiency and offered suggestions for upgrading them. From 1980 to 1981, the Oil Refit Option Qualification Field Test Program investigated and evaluated additional options in the market.[21]

Flame-retention-head oil burners were commercially available by the mid-1970s as an energy saving device but had not achieved significant market penetration despite the first energy price shock in 1973; by 1986 flame-retention-head burners

---

[20] See Batey et al. (1978), McDonald et al. (1979), and McDonald et al. (1980). Butcher et al. (1992) report average fuel savings of 15% when only the burner is replaced, increasing to as much as 40% savings when the entire heating unit is replaced.

[21] See Brookhaven Bulletin, September 18, 1981 and June 18, 1982. Accessed at https://www.bnl.gov/bnlweb/pubaf/bulletin/1947-1995/1981/18091981.pdf and https://www.bnl.gov/bnlweb/pubaf/bulletin/1947-1995/1982/18061982.pdf, most recently on June 26, 2017.

were standard on virtually all new furnace and boiler installations.[22]

1980 Newspaper Advertisement for Project Oilheat

To quantify the additionality of BTO R&D activities, it is necessary to characterize what would have happened without the BTO activities. Specifically, what would have been the diffusion trend of the flame-retention-head oil burner without Project Oilheat? By comparing this counterfactual diffusion trend with the actual diffusion trend, we can estimate that impact attributable to BTO.

3.2 SAMPLE OF INTERVIEWEES

To construct realistic counterfactual diffusion trends, we spoke with experts familiar with BTO R&D activities, other contributing factors, and the oil heating market generally.

[22] See Brown et al. (1989).

Initially, a set of eight preliminary scoping interviews were conducted for the flame-retention-head oil burner, to help design a formal interview guide for a larger number of interviews, as was done for the other two technology areas. However, a round of additional formal interviews was foregone for a number of reasons. The BTO activities and the impacts attributable to those activities were completed a relatively long time ago (36 to 40 years), the flame-retention-type burners accounting for 100% of all new burners by the late 1980s. The experts with whom we spoke, when asked for their recommendations of other individuals with first-hand knowledge of the program, frequently told us of colleagues from that time who had since retired. Several told us of colleagues who had passed away.

A summary of qualitative and quantitative findings from those eight scoping interviews was shared with those same eight individuals, which they were asked to confirm or revise. The following section summarizes qualitative insights gleaned from the original eight interviews and the round of follow-up conversations.

3.3 SUMMARY OF QUALITATIVE FINDINGS

The following qualitative statements are representative of the range of views shared by these experts in interviews:

- ***The lab testing was impactful. The field testing was extremely impactful.*** The field testing had a greater direct impact on the market, demonstrating that the FRHOB worked in realistic settings. The lab testing was crucial in that it identified the FRHOB as a promising technology from among several candidate technologies. A second crucial contribution of the lab testing was to explain where energy savings were coming from—to understand the mechanism of why the FRHOB had the impact it did.

- ***Independent third-party testing was key***. The key thing that helped to accelerate adoption of the FRHOB technology was the thorough, independent, impartial testing, verification, and documentation of results by a national lab. The results were unassailable.

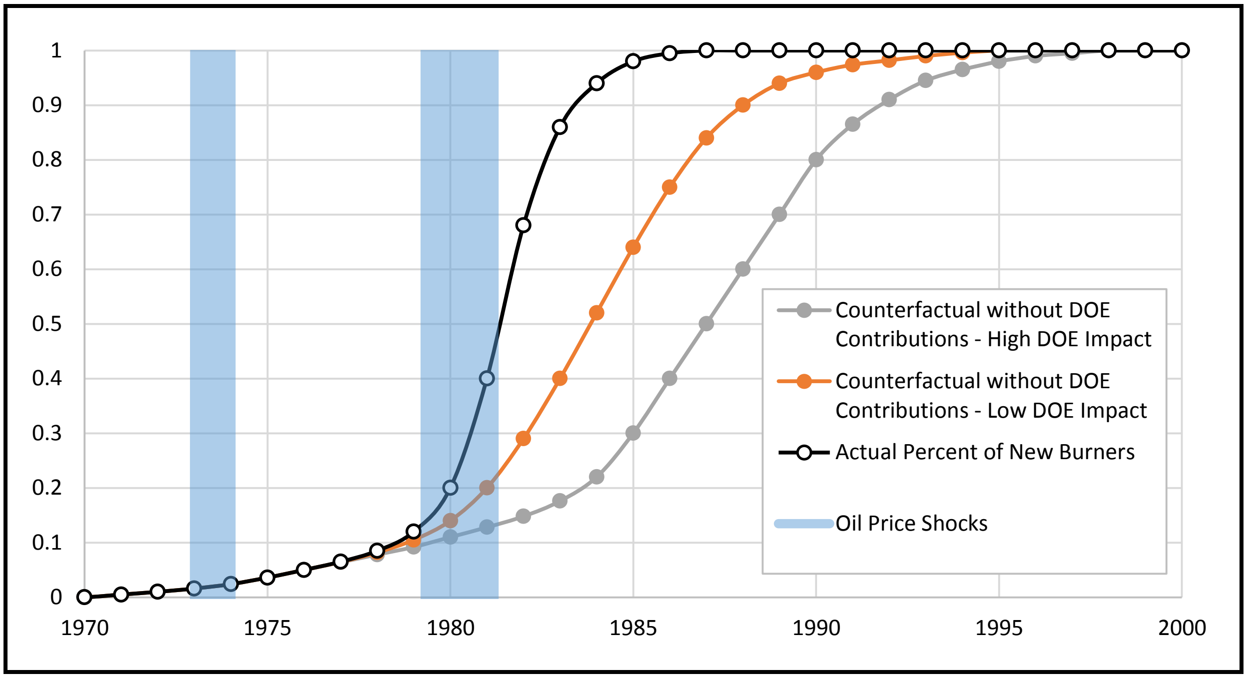
- ***Collaboration among Brookhaven National Laboratory, equipment manufacturers, and fuel oil marketers was a key to success.*** Equipment manufacturers provided equipment for testing and fed test results back into their product development to improve energy efficiency. BNL staff working directly with manufacturers and installers helped to overcome the industry's cautious tendencies toward adopting new technology. One question raised at the time was the best way to incentivize burner installers (who were typically connected with an oil supplier) to promote a higher efficiency burner, which would reduce the demand for oil and thus tend to reduce suppliers' revenues. The problem was ultimately solved by a combination of consumer demand for improved efficiency and the ability of dealers to address that demand by marketing the more efficient burners to consumers based on the impartial data produced by the national labs.

- ***Oil price shocks undoubtedly played a role.*** The second oil price shock in 1979-1981 is certainly part of the story, but it is not the whole story by any means. Without BTO, the transition to FRHOB would have been more gradual.

3.4 SUMMARY OF QUANTITATIVE FINDINGS

Figure 3-1 shows the market penetration trend for flame-retention-head burners under three scenarios: the actual trend (scenario 1) and two possible counterfactual trends (scenarios 2 and 3) representing alternative diffusion paths that might have been observed without the BTO R&D contributions discussed above. Scenarios 2 and 3 reflect the range of responses experts shared in the scoping interviews when asked to describe what the adoption trend would have looked like without BTO. Most described the trend in words. Two drew the curves. The shaded bands indicate oil price shocks.

Figure 3-1. Percentage of New Burners Sold of Flame-Retention Type, Actual and Counterfactual (without BTO)



Note: Counterfactual trends are based on interviews with experts familiar with BTO's activities, other contributing factors, and the oil heating market generally. The actual trend is a best estimate, based on Brown et al. (1989) and input from the experts interviewed. Specifically, the actual trend line was drawn to hit 100% in 1986, based on Brown et al.: "As of 1986, the three major manufacturers of oil burners manufacture and sell only FRHOBs" (p. 55). This, combined with the fact that the "FRHOB is a low technology, standard item" (Brown et al., 1989, p. 57) led us to conclude that it was unlikely any manufacturers were still producing non-flame-retention burners by 1986. Experts interviewed agreed that flame-retention burners were the industry standard by 1986.

Scenario 1: Actual Percentage of New Burners Sold (black line). The black line reflects our best estimate of the percentage of new burner installations that were the flame-retention-head type.

Scenario 2: Low DOE Impact (orange line). This scenario represents the perspectives of experts who offered a more conservative assessment of the impact of the DOE contributions.

Scenario 3: High DOE Impact (gray line). This scenario represents the perspectives of experts who attributed greater impact to the DOE contributions.

The impact attributed to BTO is represented by the difference between the actual and counterfactual trends. Thus, the level of impact attributed to DOE becomes greater as the counterfactual trend is displaced farther from the actual, reflecting a more gradual hypothesized diffusion of flame-retention type burners hypothesized in the absence of BTO R&D. The actual and counterfactual trends do not diverge before 1977.

To validate the range of impacts attributed to BTO, a version of Figure 3-1 was shared back with the experts with whom we spoke. We asked these experts to weight all three scenarios according to their relative likelihood in the absence of the DOE research contributions. Although all of the experts thought that BTO had had at least some impact on the adoption of FRHOB technology, we allowed them to assign some weight to the Actual trend, to indicate a level of impact below that of the low-impact scenario. For example, if one thought the most likely scenario, without BTO contributions, should lie half way between the "Actual" and the "Low DOE Impact" scenarios, one could allocate 50% weight to each of these two scenarios.

Six of the eight individuals responded and three of these provided weights. Two simply assigned 100% weight to the High DOE Impact scenario (essentially reiterating the points of view they had expressed in the first round of interviews). The third assigned 1% to Actual (or no DOE impact), 9% to Low Impact, and 90% to High Impact. The three who did not provide weights indicated that the high and low scenarios described a reasonable range of possibilities. Rather than use the weighted average of the scenarios, we keep the high and low scenarios as our upper and lower bounds; the fact that three respondents strongly favored the high-impact scenario gives us confidence that in doing so we are not overstating the BTO impact as perceived by these experts.

3.5 ENERGY AND RESOURCE BENEFITS

This section develops estimates for the amount of oil saved, attributable to BTO, based on the difference between actual and counterfactual trends summarized in Section 3.4. Estimates are developed in steps, explaining all assumptions, so that all calculations can be readily understood.

Step 1. First, the diffusion trends described in Figure 3-1 are converted into estimates of actual and counterfactual percentages of all operating residential oil burners that are the flame-retention type (Figure 3-2). We use the actual number of oil-heated households reported by EIA (2011, Table 2.7) and base estimates of new burner sales on the number of older burners reaching the end of their life in a given year and the change in the number of oil-heated households between that year and the last. For example, if 1 million older burners are retired in a year when the number of oil-heated households falls by 600,000, then 400,000 new burners must be purchased. The number of burners retired in each year is not known and estimates were made based on assumptions about the typical life of a burner.

Complicating these assumptions, the number of households heating with oil peaked at 17.2 million in 1973 and fell to 12.4 by 1985 (EIA, 2011, Table 2.7). Simple assumptions about the life of a burner (such as attributing a constant life of anywhere between 15 and 20 years to all burners) therefore resulted in unrealistic outcomes, such as negative sales of new burners in some years and unrealistically high sales in other years. Brown et al. (1989) and Butcher et al. (1992) report new burner sales of roughly 400,000 to 500,000 per year in the 1980s. To approximate these figures, it was necessary to assume a distribution for burner life. For most years, all burners were assumed to last through 10 years, 99.5% survived at least 11 years; 98.5% survived at least 12 years, 96.5% survived at least 13 years, 92.5% survived at least 14 years, 84.5% survived at least 15 years, 72% survived at least 16 years, 57.5% survived at least 17 years, 42.5% survived at least 18 years, 28% survived at least 19 years, 15.5% survived at least 20 years, 7.5% survived at least 21 years, 3.5% survived at least 22 years, 1.5% survived at least 23 years, 0.5% survived 24 years and expired in their 25th year. To avoid unrealistically high or low numbers of new burners in some years, it was necessary to use somewhat more aggressive attrition rates for 1974 through 1985.[23]

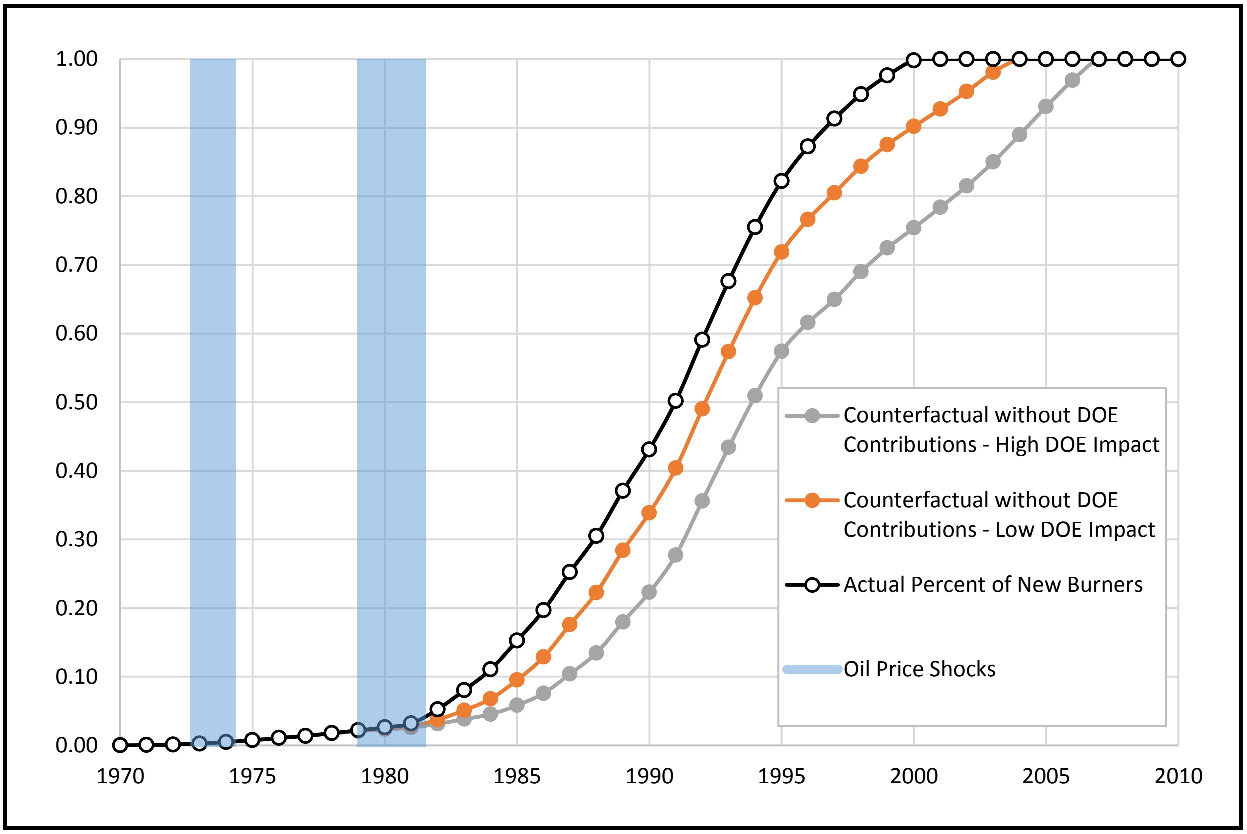
Our assumptions produce total numbers of flame-retention burners in use that are consistent with Brown et al. (1989), namely "well over 2,000,000 in 1985" (p. 55), and Butcher et al. (1992), namely "5 million flame-retention oil burners in use today representing about 45% of the oil-heated homes in the U.S.A" (p. 1). We have 1.9 million flame retention burners in

[23] Specifically, this was done to avoid negative numbers for 1980 and 1981, when the number of oil-heated homes fell most sharply (we estimate 240,000 and 170,000 new burners in those years), and to avoid unrealistically high numbers of new burners when the number of oil-heated homes levels off from 1984 to 1989 (we estimate 750,000 new burners in 1987, 630,000 in 1988, and 790,000 in 1989). Detailed figures are available from the authors.

1985 (15% of oil-heated homes), becoming 2.5 million in 1986, and 5.2 million in 1990 (43% of oil-heated homes).

Step 1 is summarized in Table 3-1 and Figure 3-2. Note that the actual and counterfactual trends do not diverge before 1977. The years 1971 to 1976 are included to show the percentage of new burners of the flame-retention type for all years for which it is assumed to be strictly positive.

Figure 3-2. Percentage of Operating Burners of Flame-Retention Type, Actual and Counterfactual (without DOE)



Note: Percentages of operating burners are based on the percentage of new burners of flame-retention type (Figure 3-1) and additional assumptions about the distribution of burners' lifespans. Our assumptions produce total numbers of flame-retention burners in use that are consistent with Brown et al. (1989), namely "well over 2,000,000 in 1985" (p. 55), and Butcher et al. (1992), namely "5 million flame-retention oil burners in use today representing about 45% of the oil-heated homes in the U.S.A" (p. 1). We have 1.9 million flame retention burners in 1985 (15% of oil-heated homes), becoming 2.5 million in 1986, and 5.2 million in 1990 (43% of oil-heated homes). Details are available from the authors.

Table 3-1. Actual and Counterfactual Percentage of Burners of Flame-Retention Type

	Percentage of New Burners			Percentage of Operating Burners		
Year	Actual	Low Counterfact.	High Counterfact.	Actual	Low Counterfact.	High Counterfact.
1971	0.50	0.50	0.50	0.04	0.04	0.04
1972	1.00	1.00	1.00	0.13	0.13	0.13
1973	1.60	1.60	1.60	0.27	0.27	0.27
1974	2.40	2.40	2.40	0.49	0.49	0.49
1975	3.60	3.60	3.60	0.75	0.75	0.75
1976	5.00	5.00	5.00	1.07	1.07	1.07
1977	6.50	6.45	6.40	1.39	1.39	1.38
1978	8.50	8.20	7.80	1.77	1.76	1.74
1979	12.00	10.50	9.20	2.19	2.13	2.06
1980	20.00	14.00	11.00	2.61	2.44	2.33
1981	40.00	20.00	12.80	3.20	2.78	2.58
1982	68.00	29.00	14.80	5.26	3.74	3.13
1983	86.00	40.00	17.60	8.03	5.11	3.83
1984	94.00	52.00	22.00	11.06	6.79	4.54
1985	98.00	64.00	30.00	15.26	9.53	5.83
1986	99.50	75.00	40.00	19.67	12.87	7.59
1987	100.0	84.00	50.00	25.26	17.60	10.40
1988	100.0	90.00	60.00	30.50	22.26	13.47
1989	100.0	94.00	70.00	37.10	28.39	17.99
1990	100.0	96.00	80.00	43.12	33.86	22.29
1991	100.0	97.40	86.50	50.17	40.38	27.73
1992	100.0	98.20	91.00	59.09	49.03	35.61
1993	100.0	99.00	94.50	67.64	57.38	43.44
1994	100.0	99.60	96.50	75.52	65.19	50.91
1995	100.0	100.0	98.00	82.22	71.89	57.40
1996	100.0	100.0	99.00	87.23	76.63	61.61
1997	100.0	100.0	99.50	91.31	80.50	64.97
1998	100.0	100.0	100.0	94.85	84.37	69.01
1999	100.0	100.0	100.0	97.60	87.53	72.46
2000	100.0	100.0	100.0	99.80	90.18	75.41
2001	100.0	100.0	100.0	100.0	92.70	78.39
2002	100.0	100.0	100.0	100.0	95.27	81.51
2003	100.0	100.0	100.0	100.0	98.09	85.01
2004	100.0	100.0	100.0	100.0	100.0	88.98
2005	100.0	100.0	100.0	100.0	100.0	93.07
2006	100.0	100.0	100.0	100.0	100.0	96.91
2007	100.0	100.0	100.0	100.0	100.0	100.0
2008	100.0	100.0	100.0	100.0	100.0	100.0
2009	100.0	100.0	100.0	100.0	100.0	100.0
2010	100.0	100.0	100.0	100.0	100.0	100.0

Notes: Percentages of new burners are the numbers underlying Figure 3-1. Percentages of operating burners (shown in Figure 3-2) are based on the percentages of new burners average and additional assumptions about the distribution of burners' lifespans. Our assumptions produce total numbers of flame-retention burners in use that are consistent with Brown et al. (1989), namely "well over 2,000,000 in 1985" (p. 55), and Butcher et al. (1992), namely "5 million flame-retention oil burners in use today representing about 45% of the oil-heated homes in the U.S.A" (p. 1). We have 1.9 million flame retention burners in 1985 (15% of oil-heated homes), becoming 2.5 million in 1986, and 5.2 million in 1990 (43% of oil-heated homes). Details are available from the authors. The actual and counterfactual trends do not diverge before 1977.

Step 2. Next, counterfactual consumption of No. 2 Heating Oil is derived from its actual consumption and the actual and counterfactual percentages of operating burners that are the flame-retention type. These calculations are based on the following assumptions:

Assumption 1: No. 2 heating oil sales account for 98% of U.S. total distillate sales to residential customers (EIA, 2016a).

Assumption 2: Average heating load is the same for burners of both types, flame-retention and not.

Assumption 3: On average, each flame-retention burner saves 16% of the fuel that would have been consumed by a non-flame-retention burner. Although Batey et al. (1978), McDonald et al. (1979), McDonald et al. (1980), and Butcher et al. (1992) cite wider ranges of estimated improvements, a range of 11% to 22% and an estimate of 16% has become generally accepted (Batey, 2013). Analysis of the sensitivity of the results to this assumption is provided in Section 9.1.

Under assumption 2, average fuel consumption (*C*) is related to the average fuel consumption of non-flame-retention burners (*X*), the percentage of operating burners that are the flame-retention type (*P*) and the average savings achieved by the flame-retention burners (Δ):

$$C = X(1 - P\Delta)$$

Parameter		Definition
C	≡	Average fuel consumption
P	≡	Percentage of burners that are flame-retention type
X	≡	Average fuel consumed by non-flame-retention burner
Δ	≡	Average percentage savings with flame-retention burner, assumed to be 16%

Using the above formula, the counterfactual fuel consumption in a given year, C_{XFact}, is related to the actual consumption and actual and counterfactual percentage of flame-retention type burners in that year by the following formula:[24]

$$C_{XFact} = C_{Actual}\left(\frac{1 - P_{XFact}\Delta}{1 - P_{Actual}\Delta}\right)$$

Table 3-2 shows the actual consumption of No. 2 heating oil and the counterfactual consumption, based on the above formula. The attributed savings, calculated as the difference between actual and counterfactual, and the real price of heating oil, which will be used in the next step, are also shown.

Step 3. Finally, attributed dollars saved are calculated by multiplying attributed fuel savings by the real price of heating oil year-by-year. Table 3-3 reports the amount of fuel and dollars saved in each year, together with undiscounted totals for all years. The middle counterfactual scenario is a simple average of the low and high counterfactual scenarios. Our estimates attribute savings to BTO of between 2.2 billion and 5.4 billion gallons of heating oil and between $4.1 billion and $10.0 billion undiscounted dollars.

Mainly because of the effort made here to quantify a counterfactual diffusion trend without BTO, the estimated impacts are lower than earlier studies have suggested. We briefly review these studies here.

Brown et al. (1989) provides an excellent overview of the technology and the BTO role and provides estimates of fuel savings. But these estimated savings are associated with the flame-retention-head burner itself, not with impacts specifically attributed to BTO (as if the counterfactual is, implicitly, that no flame-retention-type burners would have been installed). For example, whereas Brown et al. (1989, p. 56, Figure 4.3) estimate 300 million gallons of oil saved in 1984 and 550 million gallons saved in 1987, we have estimated only between 56 million and 85 million gallons saved in 1984 and between 102 million and 199 million gallons saved in 1987—*attributed to BTO*.

[24] This relationship holds because the ratio of *C* to the quantity $1 - P\Delta$ is always equal to X, which is assumed to be constant to simplify calculations.

Table 3-2. Actual and Counterfactual Residential Consumption of No. 2 Heating Oil, and Derived Savings Attributed to BTO.

	Consumption (thousands of gallons)			Attributed Savings (thousands of gallons)		Real price
Year	Actual	Low Counterfact.	High Counterfact.	Low Counterfact.	High Counterfact.	2015 dollars per gallon
1977	10,204,014	10,204,051	10,204,088	37	74	2.15
1978	10,604,946	10,605,207	10,605,541	260	595	2.10
1979	9,831,008	9,832,049	9,833,054	1,042	2,046	2.65
1980	9,884,913	9,887,572	9,889,407	2,658	4,493	3.99
1981	9,273,708	9,279,880	9,282,961	6,173	9,254	5.32
1982	8,750,862	8,772,224	8,780,836	21,362	29,975	4.50
1983	8,016,334	8,054,290	8,071,025	37,956	54,691	4.01
1984	8,051,408	8,107,419	8,136,892	56,012	85,485	3.79
1985	7,573,496	7,644,728	7,690,673	71,232	117,177	3.41
1986	7,936,526	8,025,718	8,094,919	89,192	158,393	1.74
1987	8,015,551	8,117,911	8,214,209	102,360	198,658	2.07
1988	8,348,482	8,464,224	8,587,610	115,742	239,128	1.62
1989	8,475,656	8,601,251	8,751,244	125,594	275,588	1.95
1990	7,131,818	7,245,278	7,387,072	113,460	255,255	2.34
1991	6,640,077	6,753,228	6,899,353	113,151	259,276	1.87
1992	7,145,615	7,272,709	7,442,145	127,094	296,530	1.65
1993	7,141,452	7,272,864	7,451,542	131,412	310,090	1.57
1994	7,088,078	7,221,309	7,405,456	133,230	317,377	1.51
1995	6,722,590	6,850,552	7,029,924	127,961	307,333	1.44
1996	6,771,818	6,905,340	7,094,519	133,522	322,701	1.67
1997	6,400,788	6,530,351	6,716,614	129,564	315,826	1.59
1998	5,703,560	5,816,373	5,981,533	112,813	277,973	1.34
1999	6,176,417	6,294,355	6,470,810	117,938	294,393	1.36
2000	6,693,846	6,816,417	7,004,635	122,571	310,789	2.05
2001	6,510,082	6,600,569	6,778,041	90,487	267,959	1.78
2002	6,249,120	6,305,413	6,469,261	56,293	220,141	1.63
2003	6,788,529	6,813,188	6,982,405	24,660	193,877	1.95
2004	6,512,040	6,512,040	6,648,776	0	136,736	2.27
2005	6,031,372	6,031,372	6,111,015	0	79,643	2.77
2006	4,885,129	4,885,129	4,913,856	0	28,726	2.84

Notes: Actual consumption based on 98% of U.S. total distillate sales to residential customers (EIA, 2016a). Counterfactual consumption is based on the percentage of operating burners (Table 3-1) according the formulas discussed in the text. The nominal price of heating oil (from EIA, 2016b[25]) is converted to constant 2015 dollars using the Consumer Price Index for All Urban Consumers: All Items, Annual, Seasonally Adjusted.

[25] The EIA Weekly U.S. No. 2 Heating Oil Residential Price (Dollars per Gallon) was only available from 1990-2016, However, when this price was annualized, the correlation coefficient with the U.S. Crude Oil First Purchase Price (Dollars per Barrel) was 0.98. Therefore, as an approximation of the No. 2 Heating Oil Residential price before 1990, we used the ratio of the crude oil price to the heating oil price in 1990 and scaled this back using the crude oil price in previous years.

Table 3-3. BTO-Attributed Fuel and Cost Savings

	Fuel Savings (thousands of gallons)			Cost Savings (thousands of 2015 dollars)		
Year	Low	Middle	High	Low	Middle	High
1977	37	56	74	80	120	160
1978	260	427	595	547	899	1,250
1979	1,042	1544	2,046	2,764	4,097	5,430
1980	2,658	3576	4,493	10,617	14,281	17,946
1981	6,173	7713	9,254	32,866	41,068	49,269
1982	21,362	25668	29,975	96,182	115,570	134,959
1983	37,956	46324	54,691	152,127	185,664	219,202
1984	56,012	70748	85,485	212,552	268,473	324,394
1985	71,232	94205	117,177	243,039	321,419	399,799
1986	89,192	123792	158,393	155,017	215,154	275,290
1987	102,360	150509	198,658	211,437	310,895	410,352
1988	115,742	177435	239,128	187,609	287,608	387,607
1989	125,594	200591	275,588	244,923	391,174	537,426
1990	113,460	184357	255,255	265,071	430,705	596,338
1991	113,151	186214	259,276	211,887	348,704	485,521
1992	127,094	211812	296,530	209,129	348,530	487,931
1993	131,412	220751	310,090	206,639	347,120	487,601
1994	133,230	225304	317,377	201,688	341,071	480,454
1995	127,961	217647	307,333	183,855	312,716	441,577
1996	133,522	228112	322,701	222,415	379,978	537,541
1997	129,564	222695	315,826	206,423	354,802	503,180
1998	112,813	195393	277,973	151,060	261,637	372,214
1999	117,938	206165	294,393	160,210	280,060	399,911
2000	122,571	216680	310,789	251,545	444,679	637,813
2001	90,487	179223	267,959	161,349	319,576	477,802
2002	56,293	138217	220,141	91,674	225,089	358,503
2003	24,660	109268	193,877	48,157	213,384	378,612
2004	0	68368	136,736	0	154,950	309,899
2005	0	39821	79,643	0	110,320	220,640
2006	0	14363	28,726	0	40,793	81,587
Total	2,163,778	3,766,979	5,370,181	4,120,863	7,070,535	10,020,207

Notes: Attributed dollars saved are calculated by multiplying attributed fuel savings by the real price of heating oil year-by-year. Low and high estimates are based on low and high counterfactual scenarios. Middle estimates are based on a simple average of the low and high counterfactuals. Total dollars are undiscounted.

A 2002 Strategic Program Review (U.S. DOE, 2002, page 5-16, Table 5-4) estimates benefits of $7.5 billion under a "5-year" rule and $25 billion under a "10-year" rule. Both rules are based on ad hoc assumptions suggested by the National Research Council for benefits estimation. Although these rules are a creditable effort to limit BTO attribution to something less than 100%, they are ad hoc and may tend either to understate or overstate a reasonable level of attribution in any given situation. In this case, our estimates are lower, namely between $4.1 billion and $10.0 billion undiscounted 2015 dollars. Cutting off benefits after 2000 and converting to 2000 dollars to be more closely comparable to the Strategic Program

Review, we would estimate between $2.8 billion and $6.0 billion dollars in consumer energy savings attributable to BTO.

In 1988, in testimony before Congress, C. Richard Cahoon, Vice President for Policy for the Petroleum Marketers Association of America, laid out rationale advocating for continuing DOE R&D programs focused on the conservation of home heating oil. In his testimony, Cahoon cited a $10 million DOE investment in market demonstration for flame retention head oil burners carried out by Brookhaven National Laboratory (PMAA, 1988). Without providing specific assumptions, the testimony implies that DOE's (more specifically BTO's) program is responsible for $10 billion in consumer energy savings through new equipment and retrofits through the end of the next decade, which we interpret to mean through the year 2000.

In 2001, David Nemtzow, president of the Alliance to Save Energy, in testimony before the U.S. Senate used the success of the flame-retention-head oil burner to illustrate the importance of market demonstration as a policy tool for DOE. In his testimony, Nemtzow cites a retrospective estimate of $14 billion in consumer energy cost savings as of 1999 (Nemtzow, 2001).

A 1996 U.S. Governmental Accountability Office (GAO) review of a DOE report, *Success Stories: The Energy Mission in the Market Place*, released in May 1995. The GOA takes issue with the report's claim to $5 billion in consumer energy savings, objecting to DOE being credited with "the total savings resulting from consumers' use of this technology" (GAO, 1996, p.5). Our approach corrects the problem by constructing counterfactual product adoption trends that assume only a slowing in the diffusion of the technology in the absence of BTO R&D. In comparison to the $5 billion to which GAO objected, if we truncate our estimated stream of BTO-attributed benefits in 1994 and report undiscounted 1994 dollars, the benefits are between $1.7 billion and $3.3 billion.

3.6 ENVIRONMENTAL HEALTH BENEFITS

This section develops estimates for the numbers of avoided adverse health events associated with the estimated reductions in residential heating oil consumption developed in Section 3.5. Estimates are again developed in steps, explaining all assumptions, so that all calculations can be readily understood.

Unless otherwise noted, all assumptions described in this section come directly from the COBRA model, an overview of which is provided in Section 2.2.

Step 1. First, the fuel savings for each year, given in Table 3-3, are transformed into amounts of criteria pollutants abated. This is done by applying the following multipliers:

Criteria Pollutant	Multiplier
PM 2.5	· 0.83 lbs / 1000 gallons
SO2	· 42.6 lbs / 1000 gallons
NOx	· 18 lbs / 1000 gallons
VOC	· 0.7 lbs / 1000 gallons

Source: Haneke, B. H. (2001) and EPA (2017a).

Tables 3-4 and 3-5 show the total amounts of these pollutants abated, based on low, middle, and high impact scenarios.

Step 2. Next, these amounts of abated pollutants are transformed into numbers of avoided adverse health outcomes, and associated dollar values, based on the assumptions of the COBRA model. Table 3-6 summarizes these assumptions, based on 2017 emissions (as will be explained, a population deflator is used to develop comparable numbers for all other years).

Step 3. Finally, the parameters in Table 3-6 are applied to the attributed abatements in Tables 3-4 and 3-5 to obtain estimates of attributed avoided adverse health events and associated values in each year. Because the parameters in Table 3-6 are based on the United States' population in 2017, a simple population deflator is applied to each year: the ratio of the U.S. population in the given year to the U.S. population in 2017. The estimated value of all avoided adverse health events is between \$2.6 billion and \$14.6 billion, without discounting (Table 3-7).

Table 3-4. BTO-Attributed PM 2.5 and SO2 Abated

	PM 2.5 Abated (tons)			SO2 Abated (tons)		
Year	Low	Middle	High	Low	Middle	High
1977	0	0	0	1	1	2
1978	0	0	0	6	9	13
1979	0	1	1	22	33	44
1980	1	1	2	57	76	96
1981	3	3	4	131	164	197
1982	9	11	12	455	547	638
1983	16	19	23	808	987	1,165
1984	23	29	35	1,193	1,507	1,821
1985	30	39	49	1,517	2,007	2,496
1986	37	51	66	1,900	2,637	3,374
1987	42	62	82	2,180	3,206	4,231
1988	48	74	99	2,465	3,779	5,093
1989	52	83	114	2,675	4,273	5,870
1990	47	77	106	2,417	3,927	5,437
1991	47	77	108	2,410	3,966	5,523
1992	53	88	123	2,707	4,512	6,316
1993	55	92	129	2,799	4,702	6,605
1994	55	94	132	2,838	4,799	6,760
1995	53	90	128	2,726	4,636	6,546
1996	55	95	134	2,844	4,859	6,874
1997	54	92	131	2,760	4,743	6,727
1998	47	81	115	2,403	4,162	5,921
1999	49	86	122	2,512	4,391	6,271
2000	51	90	129	2,611	4,615	6,620
2001	38	74	111	1,927	3,817	5,708
2002	23	57	91	1,199	2,944	4,689
2003	10	45	80	525	2,327	4,130
2004	0	28	57	0	1,456	2,912
2005	0	17	33	0	848	1,696
2006	0	6	12	0	306	612
Total	898	1,563	2,229	46,088	80,237	114,385

Notes: Attributed pollution abatement based on fuel savings provided in Table 3-3.

Table 3-5. BTO-Attributed NOx and VOC Abated

	NOx Abated (tons)			VOC Abated (tons)		
Year	Low	Middle	High	Low	Middle	High
1977	0	1	1	0	0	0
1978	2	4	5	0	0	0
1979	9	14	18	0	1	1
1980	24	32	40	1	1	2
1981	56	69	83	2	3	3
1982	192	231	270	7	9	10
1983	342	417	492	13	16	19
1984	504	637	769	20	25	30
1985	641	848	1,055	25	33	41
1986	803	1,114	1,426	31	43	55
1987	921	1,355	1,788	36	53	70
1988	1,042	1,597	2,152	41	62	84
1989	1,130	1,805	2,480	44	70	96
1990	1,021	1,659	2,297	40	65	89
1991	1,018	1,676	2,333	40	65	91
1992	1,144	1,906	2,669	44	74	104
1993	1,183	1,987	2,791	46	77	109
1994	1,199	2,028	2,856	47	79	111
1995	1,152	1,959	2,766	45	76	108
1996	1,202	2,053	2,904	47	80	113
1997	1,166	2,004	2,842	45	78	111
1998	1,015	1,759	2,502	39	68	97
1999	1,061	1,855	2,650	41	72	103
2000	1,103	1,950	2,797	43	76	109
2001	814	1,613	2,412	32	63	94
2002	507	1,244	1,981	20	48	77
2003	222	983	1,745	9	38	68
2004	0	615	1,231	0	24	48
2005	0	358	717	0	14	28
2006	0	129	259	0	5	10
Total	19,474	33,903	48,332	757	1,318	1,880

Notes: Attributed pollution abatement based on fuel savings provided in Table 3-3.

Table 3-6. COBRA parameters for Residential Distillate Oil Combustion (rounded)

	Number of events avoided per 1,000 tons of pollutant abated				Assumed Monetary Value (2015 dollars)		
Adverse Health Event	PM 2.5	SO2	NOx	VOC	3%	7%	Undiscounted
Adult Mortality (low)	44.0	5.9	1.6	1.1	8,434,924	7,512,853	9,126,478
Adult Mortality (high)	99.7	13.4	3.7	2.6	8,434,924	7,512,853	9,126,478
Infant Mortality	0.1	0.01	0.003	0.002	9,401,680	9,401,680	9,401,680
Non-fatal Heart Attacks (low)	5.3	0.7	0.2	0.1	122,181	118,759	124,748
Non-fatal Heart Attacks (high)	49.4	6.9	1.9	1.3	122,181	118,759	124,748
Resp. Hosp. Adm.	14.2	1.7	0.5	0.4	25,663	25,663	25,663
CVD Hosp. Adm.	17.7	2.2	0.6	0.4	38,860	38,860	38,860
Acute Bronchitis	67.0	8.4	2.5	1.7	477	477	477
Upper Res. Symptoms	1,218	153.7	44.7	31.2	33	33	33
Lower Res. Symptoms	853.4	107.5	31.3	21.8	21	21	21
Asthma ER Visits	40.2	3.8	1.4	1.0	426	426	426
MRAD	37,642	4,607	1,369	961.9	68	68	68
Work Loss Days	6,352	772.1	230.4	162.1	160	160	160
Asthma Exacerbations	1,291	163.5	47.4	33.1	57	57	57

Notes: Parameters have been rounded. Undiscounted monetary values are approximated based on simple linear extrapolation from the 3% and 7% values. MRAD, minor restricted activity day.

Table 3-7. Value of All BTO-Attributed Avoided Adverse Health Events

	Value based on low numbers of adult mortality and non-fatal heart attacks (thousands of 2015 dollars)			Value based on high numbers of adult mortality and non-fatal heart attacks (thousands of 2015 dollars)		
Year	Low	Middle	High	Low	Middle	High
1977	37	56	74	84	126	168
1978	263	432	601	596	978	1,360
1979	1,065	1,579	2,093	2,409	3,571	4,733
1980	2,751	3,700	4,650	6,221	8,368	10,515
1981	6,452	8,062	9,672	14,591	18,232	21,873
1982	22,543	27,087	31,631	50,980	61,257	71,534
1983	40,419	49,330	58,241	91,409	111,560	131,712
1984	60,171	76,002	91,833	136,078	171,880	207,681
1985	77,205	102,104	127,002	174,600	230,909	287,217
1986	97,553	135,397	173,241	220,617	306,202	391,787
1987	112,960	166,095	219,230	255,460	375,625	495,791
1988	128,894	197,598	266,301	291,496	446,869	602,243
1989	141,190	225,499	309,808	319,302	509,968	700,634
1990	128,973	209,564	290,154	291,674	473,930	656,186
1991	130,342	214,505	298,668	294,770	485,105	675,441
1992	148,359	247,252	346,145	335,516	559,163	782,810
1993	155,412	261,068	366,724	351,467	590,408	829,349
1994	159,488	269,708	379,928	360,684	609,948	859,212
1995	155,003	263,643	372,282	350,542	596,230	841,919
1996	163,635	279,557	395,479	370,062	632,220	894,379
1997	160,693	276,200	391,707	363,408	624,628	885,848
1998	141,559	245,181	348,803	320,137	554,479	788,820
1999	149,691	261,672	373,653	338,527	591,773	845,020
2000	157,299	278,072	398,845	355,734	628,862	901,991
2001	117,326	232,382	347,437	265,334	525,533	785,732
2002	73,707	180,974	288,241	166,690	409,275	651,860
2003	32,593	144,418	256,244	73,708	326,603	579,498
2004	0	91,187	182,373	0	206,219	412,439
2005	0	53,606	107,211	0	121,230	242,459
2006	0	19,519	39,038	0	44,142	88,284
Total	2,565,585	4,521,447	6,477,308	5,802,095	10,225,293	14,648,492

Notes: Attributed avoided mortalities based amounts of pollutants abated and COBRA model parameters. Within each block of three columns, Low/Middle/High refers to the scenarios in Tables 3-4 and 3-5. Lower values in the left block of Low/Middle/High scenarios are based on low numbers of adult mortality and non-fatal heart attacks in Table 3-6; higher values in the right block are based on high numbers for adult mortality and non-fatal heart attacks. Each year's estimates are deflated by the ratio of the U.S. population in the given year to the U.S. population in 2017. Totals are not discounted.

3.7 ENERGY SECURITY BENEFITS

DOE-attributed fuel savings (Table 3-3) are associated with between 23 million and 60 million avoided barrels of imported crude oil (Table 3-8). The approach used to convert fuel savings into avoided crude imports is described in Section 2.3.

Table 3-8. BTO-Attributed Avoided Crude Oil Imports: Flame-Retention-Head Oil Burner

Year	Percentage of U.S. Crude Oil Supply Imported	Fuel Savings (thousands of gallons)			Avoided Crude Oil Imports (thousands of barrels)		
		Low	Middle	High	Low	Middle	High
1977	44.9%	37	56	74	0	1	1
1978	42.9%	260	427	595	2	4	6
1979	44.2%	1,042	1,544	2,046	10	15	20
1980	39.1%	2,658	3,576	4,493	23	31	39
1981	35.3%	6,173	7,713	9,254	48	60	72
1982	29.6%	21,362	25,668	29,975	141	169	197
1983	28.5%	37,956	46,324	54,691	240	293	346
1984	28.4%	56,012	70,748	85,485	354	447	540
1985	26.7%	71,232	94,205	117,177	422	558	694
1986	32.9%	89,192	123,792	158,393	651	904	1,157
1987	36.4%	102,360	150,509	198,658	827	1,216	1,605
1988	38.6%	115,742	177,435	239,128	992	1,520	2,049
1989	43.6%	125,594	200,591	275,588	1,217	1,944	2,670
1990	44.0%	113,460	184,357	255,255	1,108	1,801	2,493
1991	43.5%	113,151	186,214	259,276	1,093	1,799	2,505
1992	45.4%	127,094	211,812	296,530	1,281	2,135	2,989
1993	49.9%	131,412	220,751	310,090	1,456	2,446	3,436
1994	50.9%	133,230	225,304	317,377	1,508	2,550	3,593
1995	51.7%	127,961	217,647	307,333	1,471	2,502	3,534
1996	52.9%	133,522	228,112	322,701	1,569	2,681	3,793
1997	56.1%	129,564	222,695	315,826	1,615	2,776	3,937
1998	58.5%	112,813	195,393	277,973	1,466	2,539	3,612
1999	59.0%	117,938	206,165	294,393	1,546	2,702	3,858
2000	60.2%	122,571	216,680	310,789	1,640	2,899	4,158
2001	61.7%	90,487	179,223	267,959	1,240	2,456	3,672
2002	61.2%	56,293	138,217	220,141	765	1,878	2,992
2003	63.2%	24,660	109,268	193,877	346	1,533	2,721
2004	65.2%	0	68,368	136,736	0	990	1,981
2005	66.5%	0	39,821	79,643	0	589	1,177
2006	66.4%	0	14,363	28,726	0	212	424
Total		2,163,778	3,766,979	5,370,181	23,033	41,652	60,270

Notes: Avoided barrels of imported crude are obtained by multiplying the percentage of U.S. crude oil supply imported by the DOE-attributed fuel savings and then dividing by 45 (to convert gallons to barrels). A detailed explanation is provided in Section 2.5.

4 Advanced Refrigeration

This section describes BTO R&D related to advanced refrigeration technology and presents estimates of benefits attributable to this R&D derived from estimated impacts on residential refrigerator energy performance trends.

4.1 TECHNOLOGY OVERVIEW

The energy efficiency improvement in residential refrigerators since the first national standard was established in 1987 is remarkable: average energy use has decreased substantially, even as the average price of refrigerators has fallen, the average volume has increased, and new features have been added. In addition, refrigerants and insulating materials have been replaced by environmentally friendlier alternatives. DOE has contributed to these trends through its funding of an ongoing refrigeration R&D program at ORNL. Specific accomplishments include the following:

- Development of a more efficient compressor by Columbus Products engineers, under subcontract to ORNL in 1981. Design changes to the motor, suction muffler, and compressor valve assembly achieved a 44% reduction in energy use
- DOE funded A.D. Little to optimize the entire residential refrigerator-freezer system, including the refrigeration circuit, case design, insulation and controls. A.D. Little developed a product between 1977 and 1981, and it was introduced to the market by Amana. This product used 60% less energy than comparable conventional units.
- Under a CRADA with the Appliance Industry-Government CFC Replacement Consortium (a subsidiary of

Association of Home Appliance Manufacturers [AHAM]), from 1993 to 1998, engineers from ORNL and industry explored new technical options to improve refrigerator energy efficiency using non-CFC refrigerants. R&D addressed highly efficient variable-speed compressors, dual-evaporator designs, compact heat exchanger designs, advanced insulations, and refrigerant blends.

DOE also contributed research support to increasingly demanding energy efficiency standards and developed test methods for the energy efficiency of refrigerators.

The average energy efficiency of commercial refrigerators/freezers and supermarket refrigeration has also improved over time. Multiple unequal parallel compressors, now the industry standard for supermarket refrigeration systems, can be traced to R&D at ORNL that demonstrated potential energy savings of 15% to 26% in 1982.[26] A 1984 collaboration between ORNL and Foster-Miller Associates, H. E. Butt Grocery, and Friedrich Commercial Refrigeration led to the commercialization of an advanced system, which by the late 1990s was used by about 80% of supermarkets.

The development, with National Energy Technology Laboratory (NETL), A.D. Little, and Delfield, of a commercial refrigerator was technically successful, improving energy efficiency and reducing production cost, but was commercially disappointing in 2001 to 2003. However, by demonstrating that efficiency improvements on the order of 70% were feasible, this effort served as a model for improving commercial refrigerator efficiency and may have given impetus to the California standards adopted in 2002 and the standards subsequently adopted by Maryland, Connecticut, New York, Oregon, Rhode Island, Arizona, Washington, and New Jersey. Related with the proliferation of state standards, the first federal standard was adopted by Congress in 2005 and went into effect in 2010. The second federal standard was adopted by DOE in 2009 and went into effect in 2012. A third federal standard was adopted by DOE in 2014 and will take effect in 2017.

[26] See Baxter, 'Advances in Supermarket Refrigeration Systems, http://www.arb.ca.gov/cc/commref/adv_supmkt_ref_syst.pdf.

4.2 SAMPLE OF INTERVIEWEES

Table 4-1 summarizes the number of organizations contacted and interviewed, the number of persons contacted and interviewed, and our respective response rates; we interviewed 44 experts from 36 organizations.

To anticipate a concern, the source of contacts was not significantly correlated with attribution of impacts to BTO R&D. We also looked for correlations between BTO attribution and other respondent characteristics, including affiliation with a national laboratory, professional involvement in technical R&D efforts, an index of their familiarity with specific BTO R&D activities, and their having ever worked in manufacturing. Only one of these characteristics was found to be significant. Respondents who had worked for a manufacturer (OEM, component, or fluid manufacturing company) tended to attribute lower impact to DOE. Despite this correlation, our main quantitative findings are fairly robust to a reweighting of responses more heavily toward industry. Section 9.2 provides details.

Table 4-1. Distribution of Experts Contacted and Interviewed

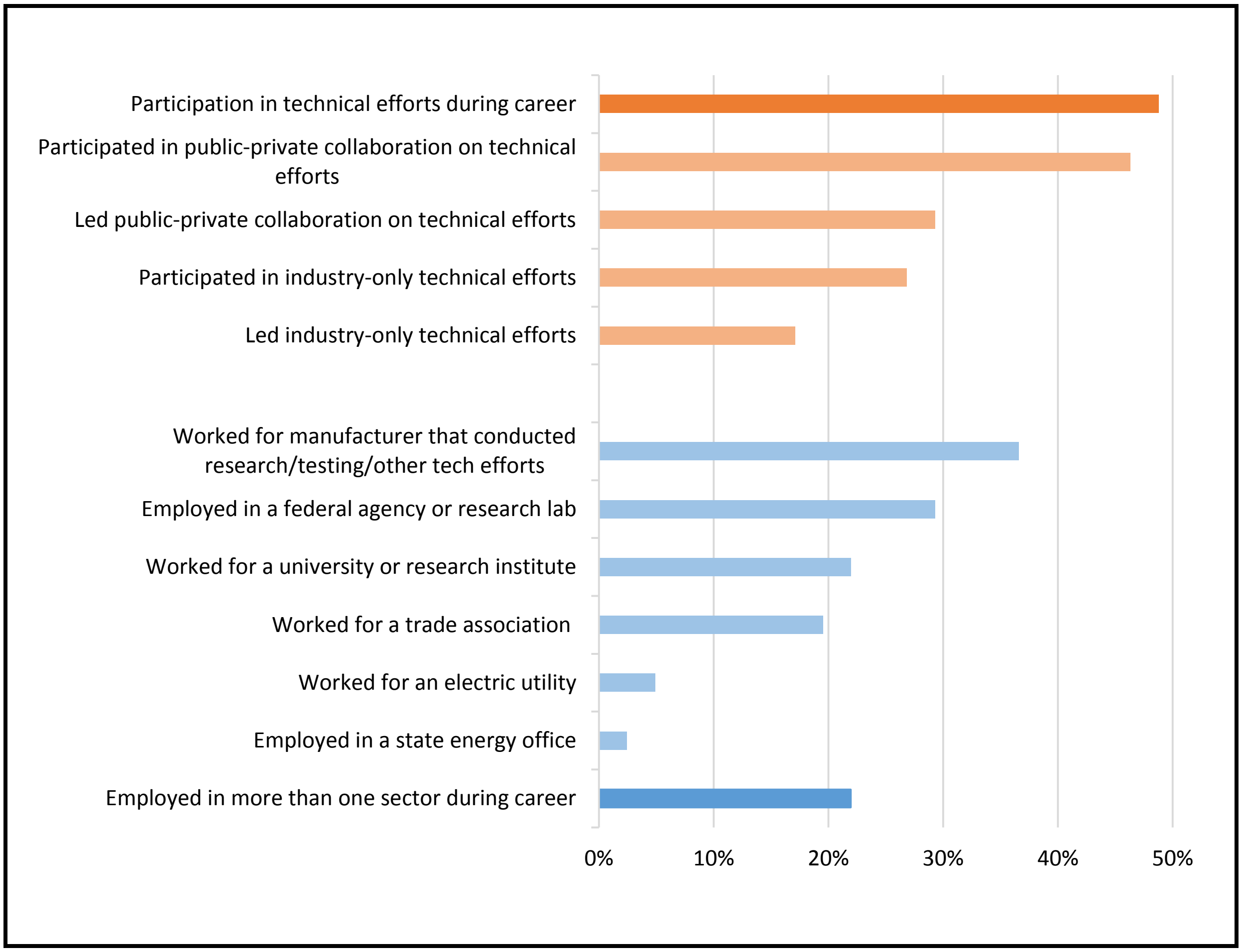
Stakeholder Group	Number of Organizations Contacted	Number of Organizations Represented in Interviews	Number of Individuals Contacted	Number of Interviews Conducted	Response Rate
Advocacy Group	10	5	21	7	33%
Federal Agency	4	3	7	4	57%
Industry/Trade Association	5	3	10	4	40%
Manufacturer	30	9	48	10	21%
National Laboratory	6	4	13	6	46%
Other	20	5	25	6	24%
University	15	7	20	7	35%
Total	90	36	144	44	31%

.

Our highest response rate came from current employees of federal agencies and DOE national laboratories with 57% and 46% response rates respectively. We had the lowest overall response rate from manufacturers at only 21%.

We also tried to capture the career experiences of interviewees across various sectors as well as involvement in public and private technical efforts which is summarized in Figure 4-1. Nearly half of interviewees had participated in some kind of public or private technical efforts during their careers. We found that there was a fairly low degree mobility across the various sectors we asked about during our interviewees' careers; only 21% of individuals that we interviewed had held positions in at least two of the sectors answer choices during their careers. Nevertheless, many interviewees were generally familiar with the Department of Energy; 50% of all interviewees had received some DOE funding or in-kind support (such as under a CRADA) for their work over the years.

Figure 4-1. Career Experience of Interviewees

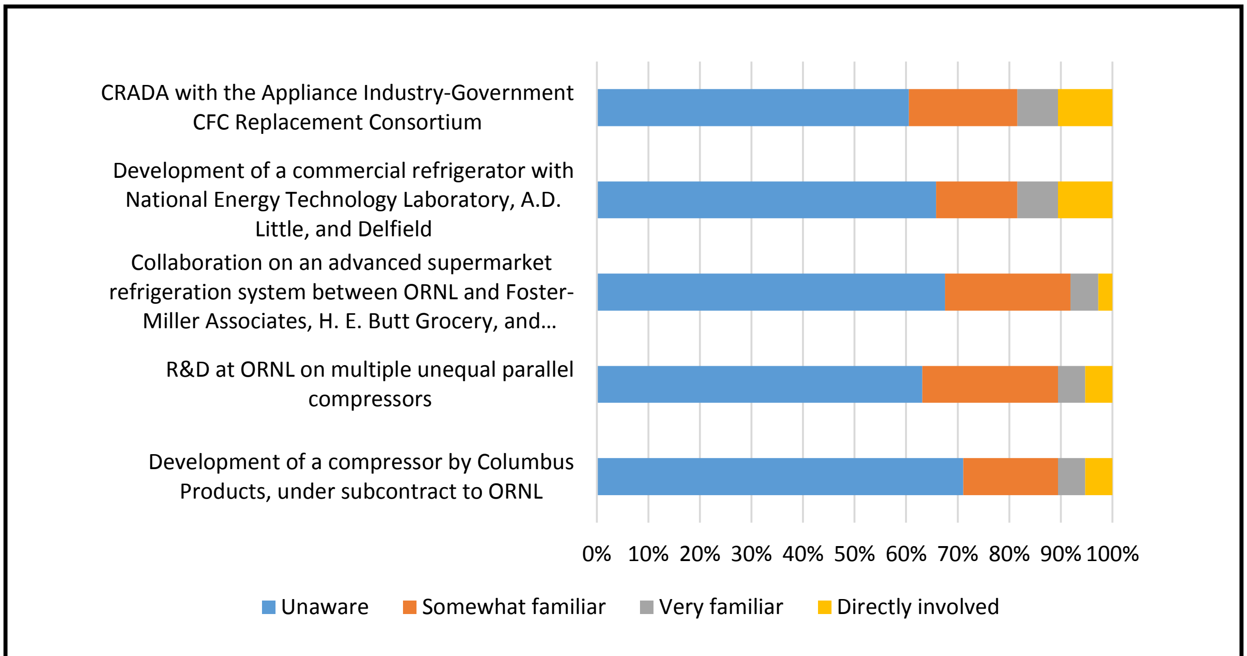


Note: A single respondent can be included in multiple categories.

For the specific set of BTO R&D projects in this part of the evaluation, we asked respondents whether they were directly involved, very familiar, somewhat familiar, or unaware. Figure 4-2 summarizes these responses. Although the figure shows that many respondents were unfamiliar with one or more of these specific DOE projects, there are several important caveats. These specific projects were highly specialized, so that respondents who had been involved in or very familiar with one were often not involved in others. More than half of our respondents were directly involved in or very familiar with at least one of these specific projects. Most respondents were at least somewhat familiar with at least one project, and all respondents were aware of DOE's role in refrigeration research and had relevant insight to share based on their experiences. People were most aware of the CRADA with the Appliance Industry-Government CFC Replacement Consortium and the R&D at ORNL on multiple unequal parallel compressors.

To some extent, individuals' lack of familiarity with these specific projects may reflect the fact that decades have passed since these projects occurred and some of the key individuals who may have been more familiar with these projects have since retired and become less accessible.

Figure 4-2. Interviewee Familiarity with Specific BTO Projects

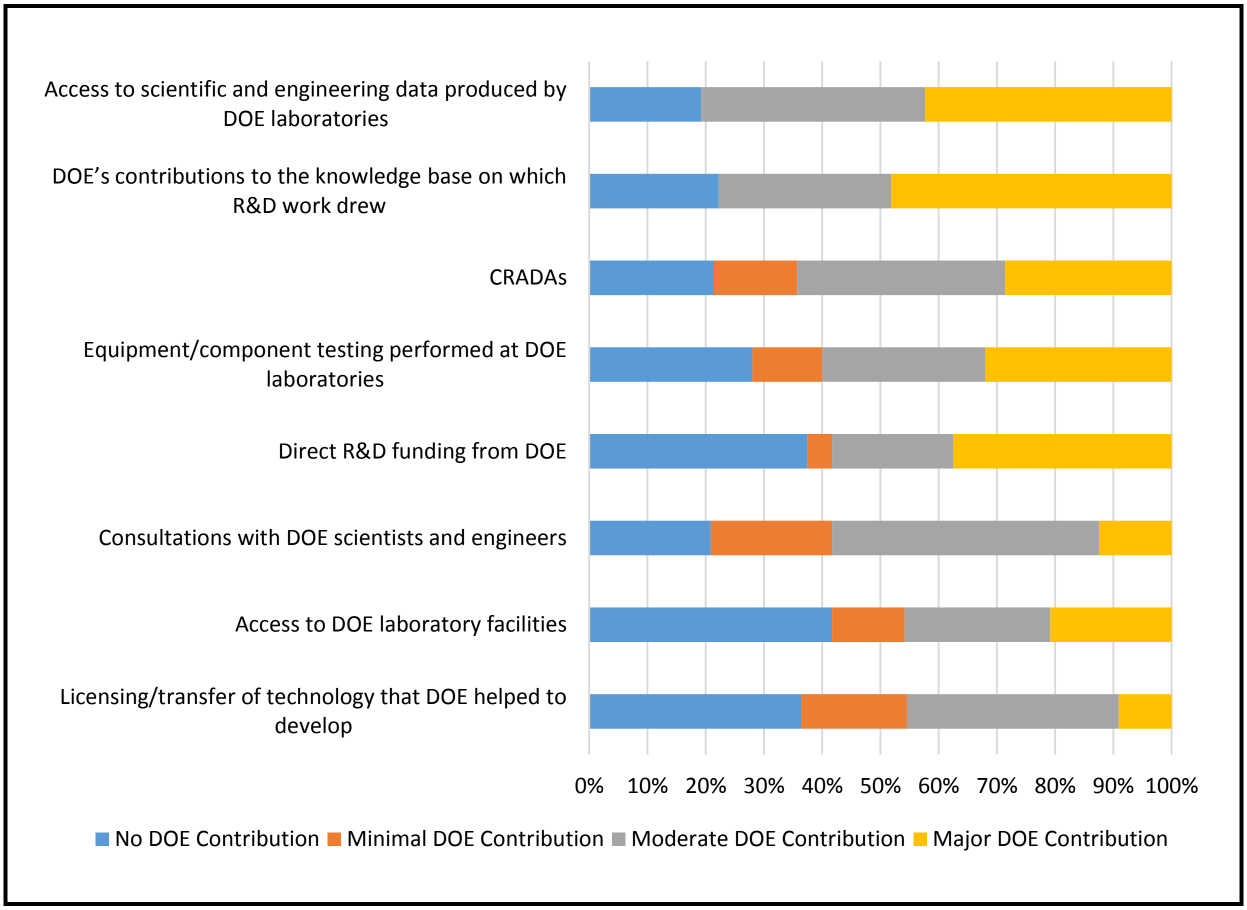


.

4.3 SUMMARY OF QUALITATIVE FINDINGS

We posed a series of structured and semi-structured questions to interviewees to understand their perceptions about the ways in which DOE research has influenced private R&D related to improving energy efficiency. Respondents in our sample rated DOE's contributions to the knowledge base and provision of scientific and engineering data as most significant. Figure 4-3 illustrates the range of opinions.

Figure 4-3. In what ways has private R&D (or your R&D work specifically) been influenced by BTO?



Note: Sorted in descending order by the combined percentage of "moderate" and "major" contribution.

Respondents expressed a variety of perspectives on how the BTO activities impact private R&D and the degree of that impact. Interviewees described direct impacts on energy efficiency that ranged from establishing credible estimates of technical potential that feeds into the standards-setting process, better-equipping refrigerator manufacturers to meet the new standards, directly improving component technologies such as compressors through collaborative research, and reducing the risk for refrigerator manufacturers to develop and adopt more efficient component technologies. Interviewees also described indirect impacts on energy efficiency such as providing knowledge and aggregating useful engineering and cost-benefit data that advocacy groups and utilities use to better design rebate and market transformation programs.

Experts in our sample considered access to scientific and engineering data produced by DOE laboratories to be highly influential, with 81% of respondents rating this a moderate or major contribution. DOE’s contributions to the knowledge base were also broadly perceived as influential; 78% of respondents assigned it a moderate or major contribution. Comments typically centered around how DOE contributions to the scientific and technical literature contributed to the knowledge base upon which standards are derived.

Among experts in our sample, 64% assigned CRADAs a moderate or major contribution. Anecdotally, there were substantial differences in the influence attributed to CRADAs for those respondents who had experience engaging in a CRADA and those that did not. Individuals who had been directly involved in a CRADA gave high rating to their importance and impact.

Asked how BTO R&D influenced either the timing or levels of energy performance standards, only a few experts characterized the counterfactual in terms of a delay in the introduction of a new standard, although most thought it not unreasonable that new standards would have been delayed in the absence of BTO R&D. Most respondents thought that the standards would have been less stringent without BTO R&D and characterized the counterfactual trends in shipments-weighted energy performance accordingly. These results are discussed in greater detail in Sections 4.4 and 4.5.

4.4 SUMMARY OF QUANTITATIVE FINDINGS

Interviewees were asked to consider how BTO R&D influenced the evolution of average energy efficiency of residential refrigerators on the market. Using interviewee input, we developed counterfactual scenarios, describing how residential refrigerator energy efficiency would have progressed in the absence of BTO R&D efforts. Many interviewees were comfortable discussing how the energy performance trend for residential refrigerators, depicted on the interview guide, would have been different without BTO R&D. These respondents described in words how the trend would have been different. If the conversation started this way, we referred back to this part of the discussion when we reached Question 14 in the interview guide (Appendix A), which asks whether average energy performance would have been different, and if so in what direction and by how much. In some cases the interviews got to Question 14 first, and in those cases we would pivot from that question to the graph of the energy efficiency trend line. To have a practicable way to combine responses, we averaged answers to Question 14 and used that average (and a range around it, based on the variability of responses) to construct the counterfactual trendline in a formulaic way, described below. We compared the range of constructed trend lines with the counterfactual trends respondents described and were satisfied that by this procedure we were not losing any meaningful information.

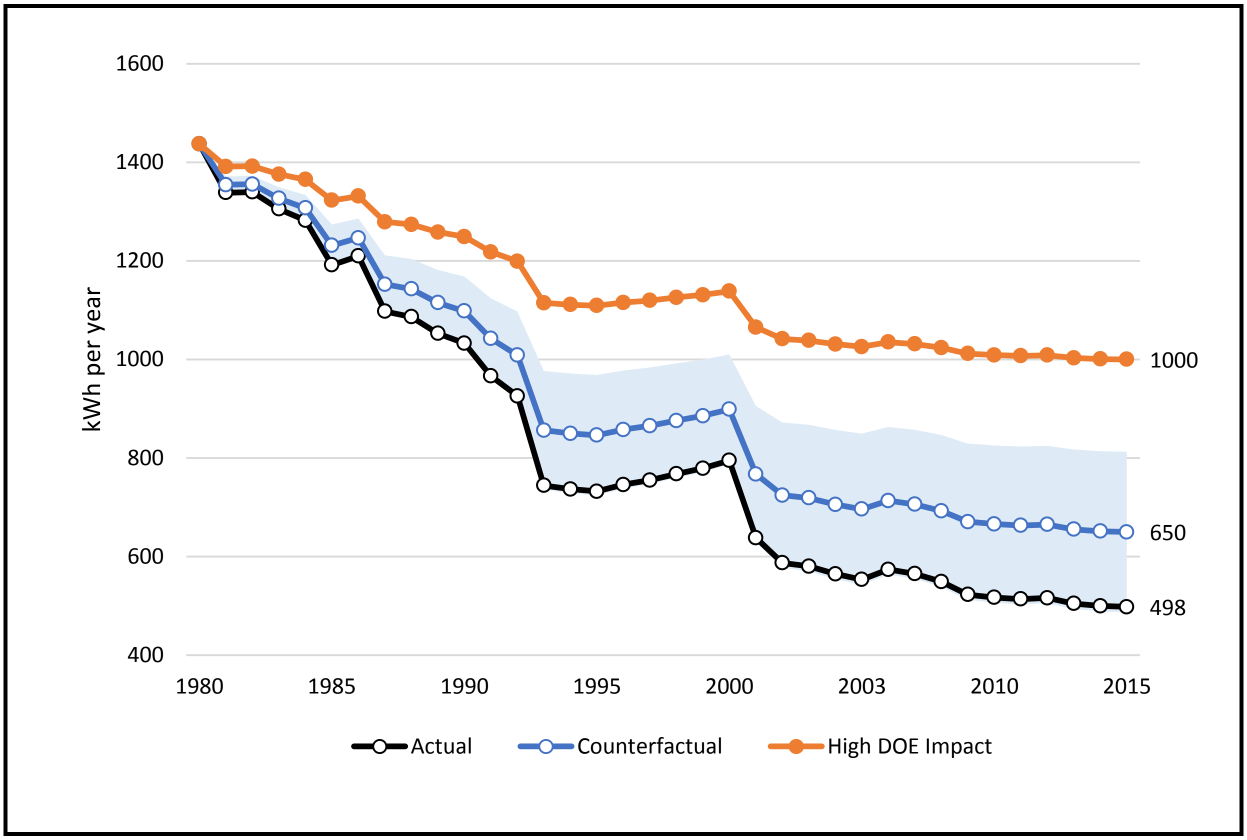
Figure 4-4 illustrates the range of responses. Some respondents expressed the opinion that the observed trend in average energy use would not be any different without DOE research. At the opposite end of the spectrum, some respondents believed that DOE research deserved credit for more than half the reduction in average energy use since 1980. This high-impact end of the range is represented by the orange trendline, falling only to 1,000 kWh by 2015.

The impact attributed to DOE is represented by the difference between the actual and counterfactual trends. Thus, the level of impact attributed to DOE becomes greater as the counterfactual trend is displaced farther from the actual, reflecting a more gradual hypothesized decline in average energy consumption in the absence of DOE research.

On average, responses put the counterfactual energy use at 650 kWh in 2015 (based on answers to Question 15 on the interview guide, Appendix A), shown by the blue trendline. This trendline was drawn as follows. First, we calculated the percentage of the drop that occurred from 1980 to 2015 attributed to DOE, based on a 2015 counterfactual value of 650: (650 – 498)/(1437 – 498) = 16%. Then, we applied the same 16% attribution to every year, attributing to DOE 16% of the difference between 1,437 kWh (the actual average usage in 1980) and the actual average usage in each year. Thus, the attributable impact in 1980 is zero, and it increases gradually, reaching (650 – 498), or 16% of (1,437 – 498), in 2015.

The shaded band around the blue trendline represents plus or minus one standard deviation of all 31 quantitative responses on which the 650 average value is based (not all interviewees provided quantitative responses).

Figure 4-4. Shipments-Weighted Average Energy Consumption of Residential Refrigerators (kWh/year), Actual and Counterfactual (without DOE)



Notes: These are shipments-weighted averages, applying only to new refrigerators purchased in each year. The high scenario reflects the opinions of those interviewees who attributed the highest impact to DOE research. The actual trendline represents the opinions of those who attributed no impact to DOE research. In between these extremes, the middle (counterfactual) scenario represents the average of all responses. The shaded band around it shows one standard deviation on either side.

The energy and resource benefits estimates developed in Section 4.5 are based on this average counterfactual trendline. The high and low bounds are based on the average, plus or minus 2.75 times the standard error (i.e., times the estimated standard deviation of the sample average), which yields a 99% confidence interval based on a *t* distribution with 30 degrees of freedom. The sample average of 650 kWh has an estimated standard deviation of 29 kWh (obtained by dividing the sample standard deviation, which is 162.9 kWh, by the square root of 31). This yields a 99% confidence interval of 570 kWh to 730 kWh in 2015. The confidence interval for the counterfactual in all other years is obtained in the same way as the average counterfactual, by holding constant the attributed percentage difference from 1,437 kWh.

4.5 ENERGY AND RESOURCE BENEFITS

This section develops estimates for the amount of energy saved, attributable to DOE, based on the difference between actual and counterfactual trends summarized in Section 4.4. Estimates are developed in steps, explaining all assumptions, so that all calculations can be readily understood.

Step 1. First, the actual and counterfactual shipments-weighted average energy usage trends described in Figure 4-4 are converted into estimates of first-year energy savings by multiplying the difference between actual and counterfactual average usage by the number of refrigerators shipped in each year. Step 1 is summarized in Table 4-2.

Step 2. Next, the cumulative energy savings in each year are calculated by summing first-year energy savings over 15-year intervals. This calculation assumes that a refrigerator is operated for 15 years and that the attributed energy savings are the same in every year. For example, the total savings in 2000 will be equal to the sum of the first-year savings in 1986 (representing the savings attributed to refrigerators purchased in 1986 that are being operated for their 15^{th} and final year in 2000), in 1987 (representing the savings attributed to refrigerators purchased in 1987 and being operated for their 14^{th} and penultimate year), in 1988, …, and in 2000.

Note that this calculation assumes that refrigerators shipped in a given year were operated for that entire year, which will tend to overstate the savings. The overestimation is relatively small.

Step 3. Finally, cumulative energy savings are converted into energy cost savings by multiplying by the real price of electricity in each year.

Steps 2 and 3 are summarized in Table 4-3. Our estimates attribute savings to DOE of between 170.5 billion and 554.3 billion kWh and between $21 billion and $68 billion undiscounted dollars.

Table 4-2. Actual and Counterfactual Average Energy Consumption and First-Year Savings

Year	Actual Avg. Usage (kWh)	Low-Impact Avg. Usage (kWh)	Mid-Impact Avg. Usage (kWh)	High-Impact Avg. Usage (kWh)	Refrig. Shipped (thous)	Low First-Year Energy Savings (GWh)	Mid First-Year Energy Savings (GWh)	High First-Year Energy Savings (GWh)
1980	1,437	1,437	1,437	1,437	5,124	0	0	0
1981	1,338	1,346	1,354	1,363	4,944	37	79	121
1982	1,340	1,347	1,355	1,364	4,364	32	69	105
1983	1,305	1,315	1,327	1,338	5,477	55	117	179
1984	1,282	1,294	1,307	1,320	5,994	71	150	230
1985	1,192	1,210	1,231	1,252	6,081	114	242	370
1986	1,210	1,227	1,247	1,266	6,510	113	240	366
1987	1,097	1,123	1,152	1,181	6,972	180	383	586
1988	1,086	1,113	1,143	1,173	7,227	193	410	628
1989	1,053	1,082	1,115	1,148	7,099	208	442	675
1990	1,033	1,064	1,098	1,133	7,101	219	465	711
1991	966	1,002	1,043	1,083	7,273	261	554	847
1992	926	965	1,009	1,052	7,761	302	642	982
1993	745	797	857	916	8,109	428	909	1,390
1994	737	790	850	910	8,652	461	981	1,500
1995	732	786	846	907	8,671	465	989	1,513
1996	746	799	858	917	9,045	476	1,012	1,547
1997	755	807	866	924	9,015	468	995	1,522
1998	768	819	876	933	9,741	497	1,055	1,614
1999	779	829	886	942	10,045	503	1,070	1,636
2000	795	844	899	954	10,169	497	1,057	1,616
2001	638	699	768	836	10,262	624	1,327	2,030
2002	587	652	725	798	10,754	696	1,479	2,262
2003	580	646	719	793	11,014	719	1,527	2,336
2004	565	631	706	781	11,953	794	1,688	2,581
2005	554	621	697	772	12,180	820	1,742	2,664
2006	574	640	714	788	12,173	800	1,701	2,601
2007	565	632	706	781	11,523	765	1,626	2,487
2008	549	617	693	769	10,312	697	1,482	2,267
2009	523	593	671	749	9,196	640	1,361	2,081
2010	517	587	666	745	10,235	717	1,524	2,330
2011	514	584	663	742	10,235	720	1,529	2,339
2012	516	586	665	744	9,493	666	1,415	2,164
2013	505	576	656	736	10,081	716	1,521	2,326
2014	500	571	652	732	10,081	720	1,529	2,339
2015	498	570	650	730	10,081	721	1,532	2,344

Notes: First-year energy savings is obtained by multiplying the number of refrigerators shipped by the difference between the actual (shipments-weighted) average usage by the counterfactual average usage. Refrigerator shipments obtained from Association of Home Appliance Manufacturers (2013).

Table 4-3. Cumulative Energy and Energy Cost Savings

Year	Low Energy Savings (GWh)	Mid Energy Savings (GWh)	High Energy Savings (GWh)	Real Price (2015 dollars /GWh)	Low Cost Savings (Millions of 2015 dollars)	Mid Cost Savings (Millions of 2015 dollars)	High Savings (Millions of 2015 dollars)
1980	0	0	0	155,344	0	0	0
1981	37	79	121	161,588	6	13	20
1982	70	148	226	169,400	12	25	38
1983	125	265	405	171,351	21	45	69
1984	195	415	635	163,039	32	68	103
1985	309	657	1,004	162,769	50	107	163
1986	422	896	1,371	160,313	68	144	220
1987	602	1,280	1,957	155,400	94	199	304
1988	795	1,690	2,585	149,881	119	253	387
1989	1,003	2,131	3,260	146,279	147	312	477
1990	1,222	2,596	3,971	142,025	174	369	564
1991	1,482	3,150	4,818	139,934	207	441	674
1992	1,785	3,792	5,800	138,676	247	526	804
1993	2,212	4,701	7,191	136,480	302	642	981
1994	2,674	5,682	8,690	133,987	358	761	1,164
1995	3,139	6,671	10,203	130,642	410	872	1,333
1996	3,578	7,604	11,630	126,310	452	960	1,469
1997	4,014	8,530	13,046	124,458	500	1,062	1,624
1998	4,455	9,468	14,481	120,091	535	1,137	1,739
1999	4,888	10,388	15,888	116,091	567	1,206	1,844
2000	5,272	11,203	17,134	113,411	598	1,271	1,943
2001	5,783	12,290	18,797	114,855	664	1,412	2,159
2002	6,299	13,386	20,473	111,206	700	1,489	2,277
2003	6,824	14,503	22,181	112,315	766	1,629	2,491
2004	7,411	15,749	24,087	112,282	832	1,768	2,705
2005	8,012	17,026	26,041	114,694	919	1,953	2,987
2006	8,551	18,173	27,794	122,285	1,046	2,222	3,399
2007	9,014	19,157	29,299	121,730	1,097	2,332	3,567
2008	9,284	19,730	30,176	123,973	1,151	2,446	3,741
2009	9,463	20,110	30,757	127,132	1,203	2,557	3,910
2010	9,714	20,644	31,574	125,411	1,218	2,589	3,960
2011	9,958	21,162	32,366	123,490	1,230	2,613	3,997
2012	10,156	21,582	33,008	122,628	1,245	2,647	4,048
2013	10,375	22,048	33,721	123,399	1,280	2,721	4,161
2014	10,591	22,507	34,423	125,348	1,328	2,821	4,315
2015	10,815	22,983	35,151	126,700	1,370	2,912	4,454
Total	170,529	362,396	554,263		20,950	44,521	68,092

Notes: Nominal energy prices are "Average Retail Price of Electricity, Residential" (dollars per kWh, including taxes) from the U.S. Energy Information Administration. Nominal prices are converted to constant 2015 dollars using the Consumer Price Index for All Urban Consumers: All Items, Annual, Seasonally Adjusted.

National Research Council (NRC, 2001) estimated the energy savings attributable to DOE (specifically BTO) R&D investments in refrigerator and freezer compressor technology from 1978 to 1981 at $7 billion, using a "5-year rule" which limits benefits to the period 1981 through 1990, with attributable impacts attenuating over time. In contrast, our approach has DOE impacts building over time, consistent with the importance, emphasized by interviewees, of the accumulation of knowledge generated by BTO R&D. To put our results in perspective, if we look only at the years 1981 through 1990, and convert to constant 1999 dollars to be consistent with NRC (2001), we estimate impacts of $0.5 billion to $1.6 billion; from 1981 through 1999, we estimate impacts of $3.0 billion to $9.8 billion. Our objective is different from that of the NRC study. While that study set out to quantify the impact of a discrete R&D project, our remit involved estimation of the cumulative impact of many formal R&D projects, as well as formal and informal interactions between DOE laboratory scientists and industry, from 1976 through 2015. Still it is interesting to note the similarity in the magnitude of impact estimates over similar timeframes.[27]

4.6 ENVIRONMENTAL HEALTH BENEFITS

This section develops estimates for the numbers of avoided adverse health events associated with the estimates of energy savings developed in Section 4.5. Estimates are again developed in steps, explaining all assumptions, so that all calculations can be readily understood. Unless otherwise noted, all assumptions described in this section come directly from the COBRA model, an overview of which is provided in Section 2.4.

Step 1. First, the energy savings for each year, given in Table 4-3, are transformed into amounts of criteria pollutants abated. This is done by applying the multipliers in Table 4-4, which are specific to the year in which the electricity was generated.

Tables 4-5 and 4-6 show the total amounts of these pollutants abated, based on low, middle, and high impact scenarios.

[27] Other studies have considered the impact of standards on energy efficiency improvements in refrigeration technology. See for example, Meyers et al. (2003) and McMahon et al. (2000). In contrast to these, we look at the impact of BTO R&D, holding the standards-setting environment constant. We thus recognize the importance of standards without explicitly measuring their impact.

Table 4-4. Average Amounts of Criteria Pollutants Released from Fuel Combustion by Electric Utilities in the United States (tons per GWh)

Year	PM 2.5	SO2	NOx	NH3	VOC
1980	0.0000	7.6297	3.0678	0.0000	0.0197
1981	0.0000	7.4977	2.9785	0.0000	0.0185
1982	0.0000	7.5701	2.9697	0.0000	0.0177
1983	0.0000	7.2406	2.8035	0.0000	0.0161
1984	0.0000	6.8244	2.6065	0.0000	0.0143
1985	0.0000	6.5799	2.4776	0.0000	0.0129
1986	0.0000	6.5046	2.5032	0.0000	0.0141
1987	0.0000	6.2621	2.4624	0.0000	0.0148
1988	0.0000	5.9297	2.3818	0.0000	0.0151
1989	0.0000	5.3862	2.2095	0.0000	0.0148
1990	0.0398	5.2370	2.1933	0.0000	0.0155
1991	0.0342	5.1350	2.1208	0.0000	0.0143
1992	0.0344	4.9989	2.1090	0.0000	0.0143
1993	0.0350	4.7507	2.0803	0.0000	0.0141
1994	0.0333	4.5847	2.0215	0.0000	0.0139
1995	0.0319	3.6022	1.9037	0.0000	0.0131
1996	0.0455	3.7069	1.7897	0.0017	0.0144
1997	0.0460	3.7785	1.7973	0.0017	0.0150
1998	0.0359	3.7058	1.7215	0.0022	0.0156
1999	0.1681	3.4057	1.5484	0.0030	0.0146
2000	0.1545	2.9973	1.4019	0.0029	0.0163
2001	0.1563	2.9038	1.3159	0.0029	0.0162
2002	0.1312	2.7047	1.2205	0.0075	0.0128
2003	0.1312	2.6635	1.1175	0.0072	0.0127
2004	0.1291	2.5814	0.9997	0.0067	0.0123
2005	0.1272	2.5655	0.9351	0.0063	0.0119
2006	0.1101	2.3484	0.8827	0.0065	0.0115
2007	0.0913	2.0898	0.8139	0.0066	0.0109
2008	0.0751	1.8916	0.7631	0.0068	0.0106
2009	0.0695	1.7118	0.7134	0.0069	0.0108
2010	0.0582	1.3809	0.5958	0.0064	0.0101
2011	0.0501	1.1281	0.5098	0.0062	0.0099
2012	0.0484	1.1423	0.4854	0.0062	0.0098
2013	0.0459	1.1369	0.4524	0.0062	0.0095
2014	0.0433	0.7876	0.4187	0.0062	0.0091
2015	0.0435	0.5518	0.3578	0.0063	0.0092

Notes: Quantities of pollutants are drawn from EPA (2017b). U.S. electric utility outputs are drawn from EIA (2017c).

Table 4-5. BTO-Attributed PM 2.5, NH3, and VOC Abated (tons)

	PM2.5			NH3			VOC		
Year	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
1980	0	0	0	0	0	0	0	0	0
1981	0	0	0	0	0	0	1	1	2
1982	0	0	0	0	0	0	1	3	4
1983	0	0	0	0	0	0	2	4	7
1984	0	0	0	0	0	0	3	6	9
1985	0	0	0	0	0	0	4	8	13
1986	0	0	0	0	0	0	6	13	19
1987	0	0	0	0	0	0	9	19	29
1988	0	0	0	0	0	0	12	26	39
1989	0	0	0	0	0	0	15	32	48
1990	49	103	158	0	0	0	19	40	61
1991	51	108	165	0	0	0	21	45	69
1992	61	130	199	0	0	0	25	54	83
1993	77	165	252	0	0	0	31	66	101
1994	89	189	289	0	0	0	37	79	120
1995	100	213	326	0	0	0	41	88	134
1996	163	346	530	6	13	20	52	110	168
1997	185	393	600	7	15	22	60	128	195
1998	160	340	519	10	21	32	69	147	225
1999	822	1,746	2,671	15	31	47	72	152	232
2000	815	1,731	2,647	15	32	50	86	182	279
2001	904	1,921	2,938	17	36	55	94	199	304
2002	826	1,756	2,686	47	100	153	81	172	262
2003	895	1,902	2,910	49	104	159	86	184	281
2004	957	2,033	3,109	50	106	161	91	193	295
2005	1,019	2,165	3,311	50	107	163	95	202	309
2006	942	2,001	3,060	55	118	180	98	209	320
2007	823	1,749	2,674	59	126	192	99	209	320
2008	697	1,481	2,266	64	135	207	98	209	319
2009	658	1,398	2,138	65	139	212	102	217	332
2010	565	1,201	1,837	62	131	201	98	208	318
2011	499	1,059	1,620	61	130	200	99	209	320
2012	492	1,045	1,598	63	135	206	99	211	322
2013	476	1,012	1,548	65	137	210	98	208	319
2014	459	975	1,491	66	140	214	97	205	314
2015	470	999	1,529	68	144	220	99	211	322
Total	13,252	28,162	43,072	894	1,900	2,906	1,999	4,249	6,499

.

Table 4-6. BTO-Attributed SO2 and NOx (tons)

	SO2			NOx		
Year	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
1980	0	0	0	0	0	0
1981	279	592	906	111	235	360
1982	526	1,119	1,711	207	439	671
1983	902	1,916	2,931	349	742	1,135
1984	1,333	2,832	4,332	509	1,082	1,654
1985	2,033	4,321	6,609	766	1,627	2,488
1986	2,743	5,829	8,916	1,056	2,243	3,431
1987	3,771	8,013	12,255	1,483	3,151	4,819
1988	4,715	10,021	15,326	1,894	4,025	6,156
1989	5,402	11,481	17,559	2,216	4,709	7,203
1990	6,398	13,596	20,795	2,680	5,694	8,709
1991	7,612	16,177	24,742	3,144	6,681	10,219
1992	8,921	18,958	28,995	3,764	7,998	12,233
1993	10,510	22,335	34,160	4,602	9,780	14,958
1994	12,259	26,051	39,843	5,405	11,487	17,568
1995	11,308	24,031	36,754	5,976	12,700	19,424
1996	13,263	28,186	43,109	6,404	13,609	20,814
1997	15,166	32,231	49,295	7,214	15,331	23,448
1998	16,511	35,088	53,665	7,670	16,299	24,929
1999	16,647	35,378	54,108	7,569	16,085	24,601
2000	15,801	33,579	51,356	7,390	15,705	24,020
2001	16,793	35,688	54,583	7,611	16,173	24,736
2002	17,037	36,206	55,375	7,688	16,338	24,988
2003	18,177	38,629	59,080	7,627	16,208	24,788
2004	19,131	40,655	62,179	7,408	15,744	24,079
2005	20,555	43,681	66,808	7,492	15,921	24,351
2006	20,082	42,677	65,272	7,548	16,040	24,533
2007	18,839	40,034	61,230	7,337	15,592	23,847
2008	17,562	37,321	57,080	7,085	15,056	23,028
2009	16,198	34,423	52,649	6,751	14,346	21,941
2010	13,414	28,507	43,600	5,788	12,299	18,811
2011	11,233	23,872	36,511	5,076	10,788	16,499
2012	11,601	24,654	37,706	4,929	10,476	16,022
2013	11,795	25,066	38,336	4,693	9,974	15,254
2014	8,341	17,726	27,111	4,434	9,424	14,413
2015	5,967	12,682	19,396	3,870	8,224	12,578
Total	382,826	813,555	1,244,283	165,744	352,227	538,710

.

Step 2. Next, these amounts of abated pollutants are transformed into numbers of avoided adverse health outcomes, and associated dollar values, based on the assumptions of the COBRA model. Table 4-7 summarizes these assumptions, based on 2017 emissions (as will be explained, a population deflator is used to develop comparable numbers for all other years).

Table 4-7. COBRA parameters for Electric Utility Fuel Combustion (rounded)

	Number of events avoided per 1000 tons of pollutant abated					Assumed Monetary Value (2015 dollars)		
Adverse Health Event	PM 2.5	SO2	NOx	NH3	VOC	3%	7%	Undiscounted
Adult Mortality (low)	8.8	3.3	0.8	1.3	0.1	8,434,924	7,512,853	9,126,478
Adult Mortality (high)	19.9	7.6	1.8	3.0	0.2	8,434,924	7,512,853	9,126,478
Infant Mortality	0.02	0.01	0.00	0.00	0.00	9,401,680	9,401,680	9,401,680
Non-fatal Heart Attacks (low)	1.1	0.4	0.1	0.2	0.01	122,181	118,759	124,748
Non-fatal Heart Attacks (high)	10.0	3.9	0.9	1.4	0.1	122,181	118,759	124,748
Resp. Hosp. Adm.	2.6	1.0	0.2	0.3	0.03	25,663	25,663	25,663
CVD Hosp. Adm.	3.2	1.2	0.3	0.4	0.04	38,860	38,860	38,860
Acute Bronchitis	12.8	4.8	1.2	2.1	0.2	477	477	477
Upper Res. Symptoms	232.7	87.6	21.0	38.8	3.0	33	33	33
Lower Res. Symptoms	162.9	61.3	14.7	27.2	2.1	21	21	21
Asthma ER Visits	5.1	1.8	0.4	0.7	0.1	426	426	426
MRAD	6,610	2,462	581	1,186	82.4	68	68	68
Work Loss Days	1,109	412.5	97.4	199.9	13.8	160	160	160
Asthma Exacerbations	246.2	92.7	22.2	41.4	3.1	57	57	57

Notes: Parameters have been rounded. Undiscounted monetary values are approximated based on simple linear extrapolation from the 3% and 7% values. MRAD = minor restricted activity day.

Step 3. Finally, the parameters in Table 4-7 are applied to the attributed abatements in Tables 4-5 and 4-6 to obtain estimates of attributed avoided adverse health events and associated values in each year. Because the parameters in Table 4-7 are based on the United States' population in 2017, a simple population deflator is applied to each year: the ratio of the U.S. population in the given year to the U.S. population in 2017. Table 4-8 reports the estimated value of all avoided adverse health events at between $12 billion and $92 billion, without discounting.

Table 4-8. Value of All BTO-Attributed Avoided Adverse Health Events

	Value based on low numbers of adult mortality and non-fatal heart attacks (millions of 2015 dollars)			Value based on high numbers of adult mortality and non-fatal heart attacks (millions of 2015 dollars)		
Year	Low	Middle	High	Low	Middle	High
1980	0	0	0	0	0	0
1981	7	14	22	15	32	49
1982	13	27	41	29	61	93
1983	22	47	71	50	105	161
1984	33	69	106	74	157	240
1985	50	107	163	113	241	369
1986	68	145	222	155	329	503
1987	95	202	309	215	457	699
1988	120	255	390	272	578	883
1989	139	296	452	315	669	1,024
1990	170	361	553	385	818	1,250
1991	204	434	664	462	982	1,502
1992	243	517	790	550	1,169	1,788
1993	292	620	948	660	1,402	2,144
1994	344	732	1,119	779	1,656	2,532
1995	328	698	1,067	743	1,579	2,415
1996	389	827	1,265	881	1,872	2,863
1997	450	956	1,462	1,018	2,162	3,307
1998	491	1,044	1,597	1,112	2,363	3,614
1999	546	1,161	1,775	1,236	2,627	4,017
2000	528	1,122	1,716	1,195	2,539	3,883
2001	568	1,207	1,846	1,286	2,732	4,178
2002	576	1,223	1,871	1,302	2,768	4,233
2003	617	1,312	2,006	1,397	2,968	4,539
2004	653	1,387	2,121	1,477	3,138	4,799
2005	704	1,496	2,288	1,593	3,385	5,177
2006	692	1,470	2,249	1,565	3,327	5,088
2007	653	1,387	2,121	1,477	3,138	4,800
2008	611	1,297	1,984	1,381	2,936	4,490
2009	571	1,213	1,855	1,291	2,744	4,197
2010	479	1,019	1,558	1,085	2,305	3,525
2011	408	867	1,326	923	1,962	3,001
2012	420	893	1,366	951	2,022	3,092
2013	426	906	1,386	965	2,050	3,136
2014	322	683	1,045	728	1,546	2,365
2015	248	528	807	562	1,194	1,826
Total	12,480	26,521	40,562	28,239	60,011	91,784

Notes: Attributed avoided mortalities based amounts of pollutants abated and COBRA model parameters. Within each block of three columns, Low/Middle/High refers to the scenarios in Tables 4-5 and 4-6. Lower values in the left block of Low/Middle/High scenarios are based on low numbers of adult mortality and non-fatal heart attacks in Table 4-7; higher values in the right block are based on high numbers for adult mortality and non-fatal heart attacks. Each year's estimates are deflated by the ratio of the U.S. population in the given year to the U.S. population in 2017. Totals are not discounted.

4.7 ENERGY SECURITY BENEFITS

DOE-attributed energy savings (Table 4-3) are associated with between 3 million and 10 million avoided barrels of imported crude oil (Table 4-9). The approach used to convert fuel savings into avoided crude imports is described in Section 2.3.

Table 4-9. BTO-Attributed Avoided Crude Oil Imports: Residential Refrigeration

Year	Percentage of U.S. Crude Oil Supply Imported	Petroleum Consumed for Electricity Generation (thousands of barrels)	Total Electricity Generation (GWh)	Avoided Crude Oil Imports (thousands of barrels)		
				Low	Middle	High
1980	39.1%	421,110	2,289,600	0	0	0
1981	35.3%	351,806	2,297,973	2	4	6
1982	29.6%	250,517	2,244,372	2	5	7
1983	28.5%	246,804	2,313,446	4	8	11
1984	28.4%	205,736	2,419,465	4	9	14
1985	26.7%	174,571	2,473,002	5	12	18
1986	32.9%	232,046	2,490,471	12	26	39
1987	36.4%	201,116	2,575,288	16	34	52
1988	38.6%	250,141	2,707,411	26	56	86
1989	43.6%	280,986	2,967,146	39	82	126
1990	44.0%	218,800	3,037,827	36	77	117
1991	43.5%	203,669	3,073,799	40	85	130
1992	45.4%	172,241	3,083,882	42	90	137
1993	49.9%	192,462	3,197,191	62	132	201
1994	50.9%	183,618	3,247,522	72	153	234
1995	51.7%	132,578	3,353,487	60	127	195
1996	52.9%	144,626	3,444,188	74	158	241
1997	56.1%	159,715	3,492,172	96	204	312
1998	58.5%	222,640	3,620,295	150	318	486
1999	59.0%	207,871	3,694,810	151	322	492
2000	60.2%	195,228	3,802,105	152	323	494
2001	61.7%	216,672	3,736,644	193	410	627
2002	61.2%	168,597	3,858,452	157	334	511
2003	63.2%	206,653	3,883,185	214	455	696
2004	65.2%	203,494	3,970,555	231	491	751
2005	66.5%	206,785	4,055,423	254	539	824
2006	66.4%	110,634	4,064,702	144	306	469
2007	66.2%	112,615	4,156,745	151	321	490
2008	66.8%	80,932	4,119,388	114	242	370
2009	62.9%	67,668	3,950,331	95	202	309
2010	62.6%	65,071	4,125,060	89	190	291
2011	60.3%	52,387	4,100,141	72	152	233
2012	56.8%	40,977	4,047,765	55	116	177
2013	50.5%	47,492	4,065,964	57	121	186
2014	46.3%	53,593	4,093,606	60	127	195
2015	45.5%	49,145	4,077,601	55	118	180
Total				2,987	6,347	9,707

Notes: Avoided barrels of imported crude in a given year are obtained by taking the product of (1) the percentage of U.S. crude oil supply imported, (2) the number of barrels of petroleum liquids consumed in electricity generation, and (3) the percentage reduction in electricity consumption attributed to DOE, and then multiplying by 42/45 (to convert barrels of refined petroleum liquids to barrels of crude). A detailed explanation is provided in Section 2.5. Percentage savings is calculated by dividing DOE-attributed savings (Table 4-3) by U.S. electric utility outputs (EIA, 2017c).

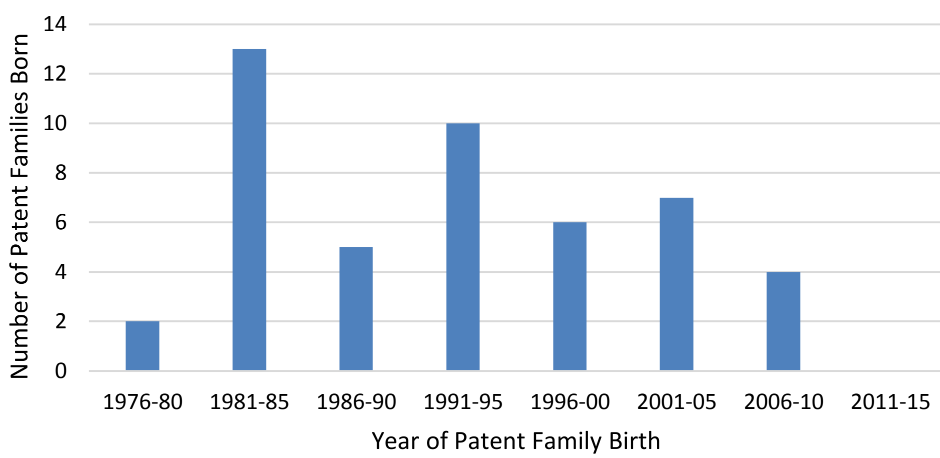
4.8 KNOWLEDGE BENEFITS

This section assesses selected knowledge benefits resulting from BTO's funding of R&D in appliances technologies, including but not limited to advanced refrigeration.

4.8.1 Trends in Attributed Patenting

Figure 4-5 shows the number of BTO-attributed appliance patent family births by year of birth. The bulk of activity occurred in the 1980s and early 1990s. Of the 47 BTO-appliance patent families, 27 were born between 1981 and 1995; only 11 families were born in 2001 or after, and there are none from 2011 on.

Figure 4-5. Trend in BTO-Attributed Appliance Patent Family Births



Note: Patent families are assigned to the year of the first patent application in the family.

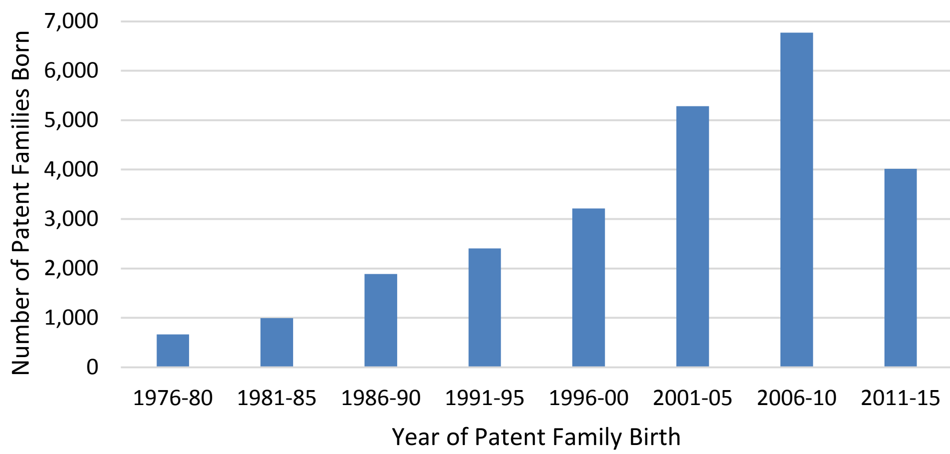
The number of appliance patent family births springing from all organizations has steadily increased over the same period (Figure 4-6).[28]

Similar to HVAC patenting trends, in tracing the influence of BTO-Appliances patents, the impact examined is largely of older, possibly foundational, BTO-attributed technologies, rather than more recent innovations. This likely impact of early

[28] The number of patent family births in 2011-2015 is biased downward by time lags in the patenting process; most patent families filed in 2015, and possibly in 2014, had not yet been issued when this analysis was carried out.

BTO-Appliance patents is supported by the forward and backward patent analysis in presented in the following sections.

Figure 4-6. Trend in All Appliance Patent Family Births



Note: Patent families are assigned to the year of the first patent application in the family.

4.8.2 Assignees of Attributed Patents

DOE is the most prolific assignee with 16 patent families, followed by DOE lab managers Lockheed Martin (9 families), and Battelle Memorial Institute and Midwest Research Institute (3 each). Other assignees that have one or two of the BTO-attributed patents include MIT, UT-Battelle, Spauschus Associates, Sonic Compressor Systems, Varitec Thermal, Procter & Gamble, ADA Technologies, Colorado State University, Brookhaven Science Associates, and Astronautics Corp.

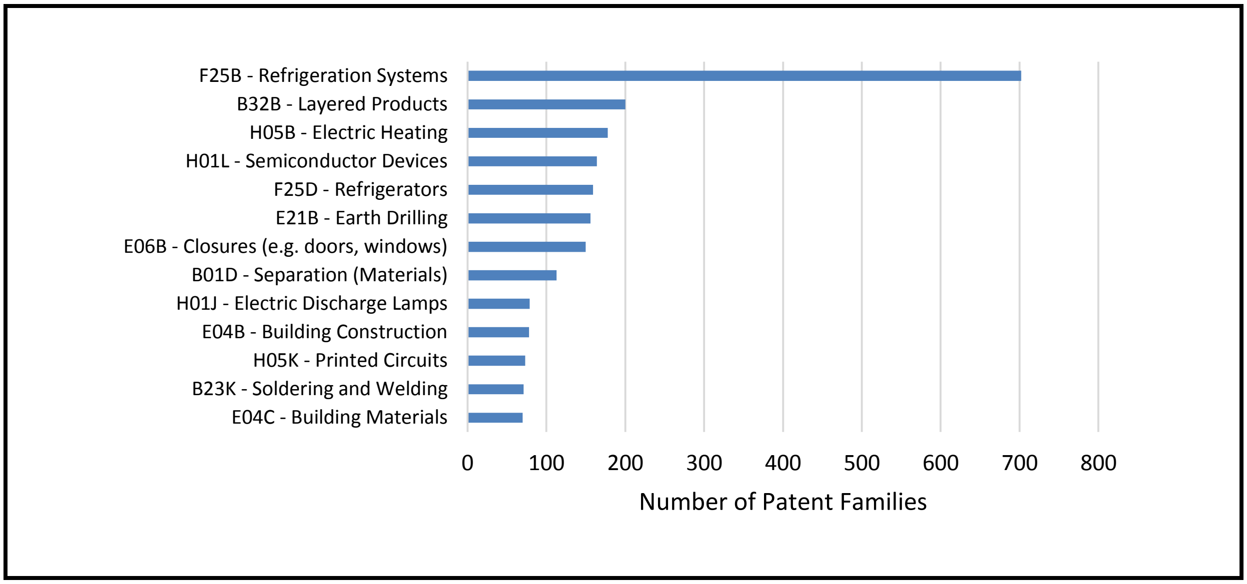
It was found that most of the Appliance research funded by DOE has been carried out in DOE labs. As in the case of HVAC, the assignees include none of the top companies leading in downstream appliance patenting.

4.8.3 Influence of Attributed Patents: Forward Tracing

This section traces forward from BTO-Appliances patents to examine the breadth of influence of the Appliances research funded by BTO. To facilitate the analysis, primary International Patent Classifications (IPCs) are used. Figure 4-7 shows the 4-digit IPCs with the largest number of patent families that cite BTO-Appliance patents directly and indirectly as prior art.

Refrigeration Systems (IPC F25B) is dominant, followed by Layered Products and Electric Heating. Adding the second level of citations increases the prominence of two other IPCs – Semiconductor Devices (H01L) and Earth Drilling (E21B)– demonstrating a knowledge spillover effect.

Figure 4-7. Patent Families Linked to BTO-Attributed Prior Appliance Patents by IPC



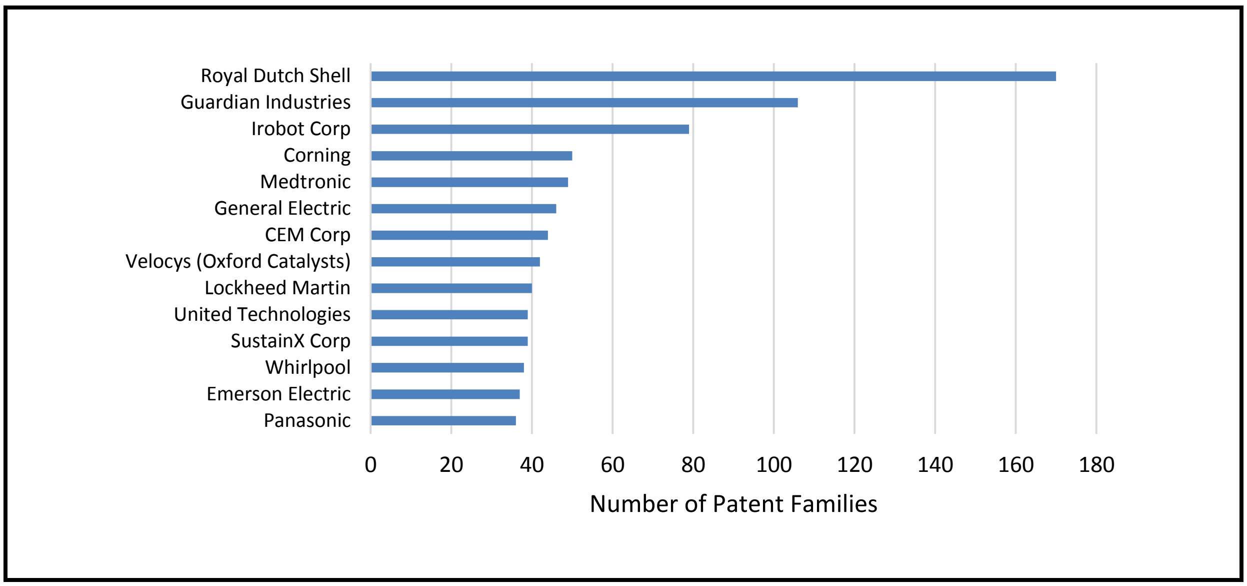
Note: IPC = International Patent Classification.

The organizations with the largest number of patent families linked directly or indirectly to earlier BTO-Appliances patents are shown in Figure 4-8. This figure includes patent families assigned to all organizations, not just the leading Appliances companies. It also includes all patent families from these organizations, not just patent families describing Appliances technology. This figure reveals that the company with the most patent families linked to BTO-Appliances patents is Shell (170 families). These Shell patents are mainly concerned with fluid heating, either for wellbores, or for hydrocarbon extraction through fracturing (often referred to as 'fracking'). They reference earlier patents related to fluid heating, which in turn reference a BTO-appliance patent (US#4,459,811) that describes heat exchange in magnetic refrigeration. This illustrates how, over just two patent generations, the influence of a patent can extend well beyond its targeted area.

The influence of BTO-Appliances patents extending beyond Appliances technology can also be seen in the identity of the companies that follow Shell in Figure 4-8. The second-placed company is Guardian Industries, whose patents linked to BTO-Appliances patents describe insulated window panels. The next three companies are iRobot, Corning and Medtronic, whose patents linked to BTO-Appliances patents that respectively describe automated vacuum cleaners, laser sealed glass packages for thin films, and use of microwave energy in medical procedures.

Only three of the leading innovative Appliances companies appear in Figure 4-8 (i.e., General Electric, Whirlpool and Panasonic). This suggests that much of the impact of BTO's Appliances patents has been on technological developments beyond those associated with the leading Appliances companies.

Figure 4-8. Organizations with the Greatest Numbers of Patent Families Linked to BTO-Attributed Prior Appliance Patents by IPC

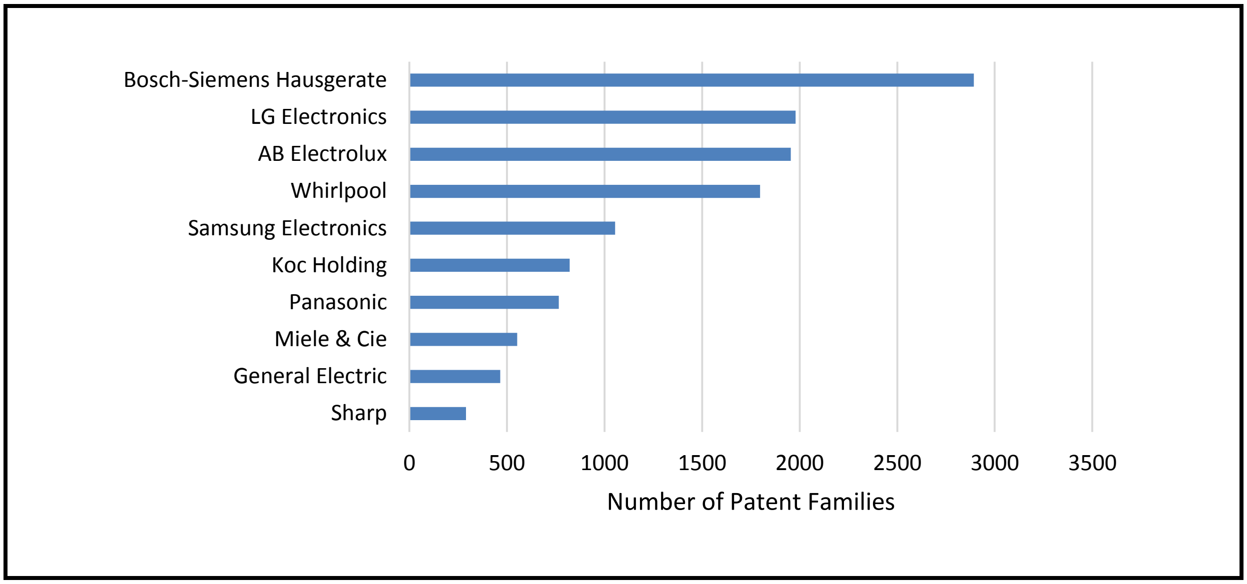


.

4.8.4 Influence of Attributed Patents: Backward Tracing

The 10 companies with the largest number of Appliances patent families are shown in Figure 4-9, where the analysis covers the following types of Appliances: refrigerators, dishwashers, washing machines, clothes dryers, stoves, and microwaves, but is not extended to cover smaller appliances due to resource requirements and complexity in assessing a very large number of appliances. The backward tracing for Appliances begins with the Appliances patent family portfolios of these companies.

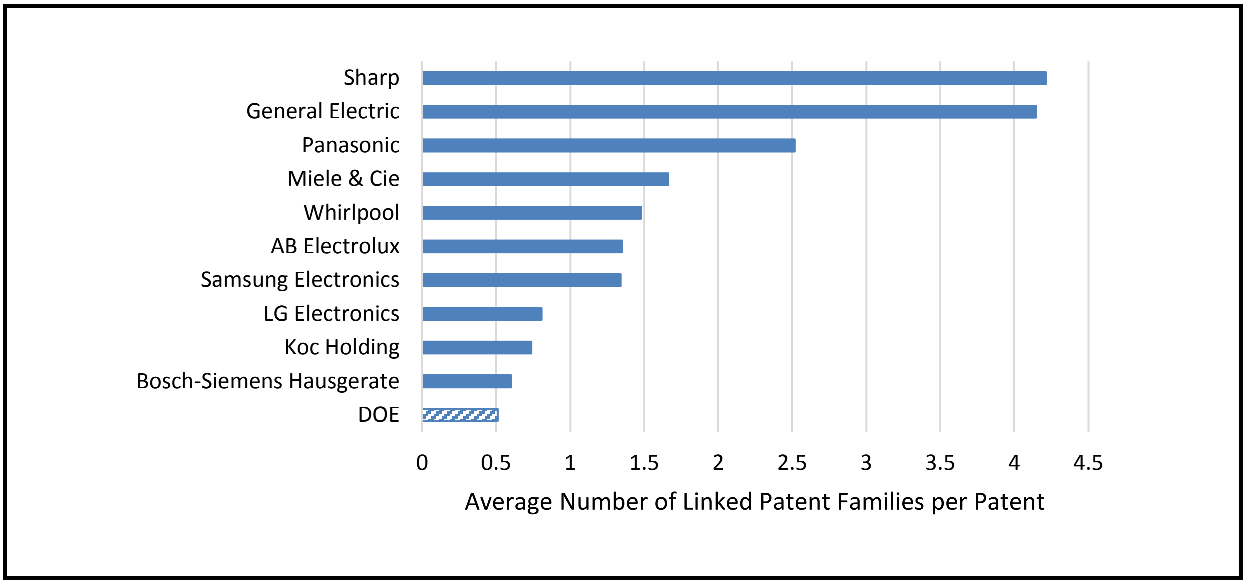
Figure 4-9. Companies with the Ten Largest Appliance Patent Portfolios



Note: For derivation of this list of companies, see Appendix B.

After adjusting for the large differences in the size of patent portfolios among the organizations by using the mean number of linked patent families, and after also removing self-citations, DOE (BTO) is at the bottom of the list in Figure 4-10, with an average of 0.51 per patent family. It is interesting to note that this is a comparable average to the two companies with the largest Appliances patent portfolios – BSH and LG Electronics.

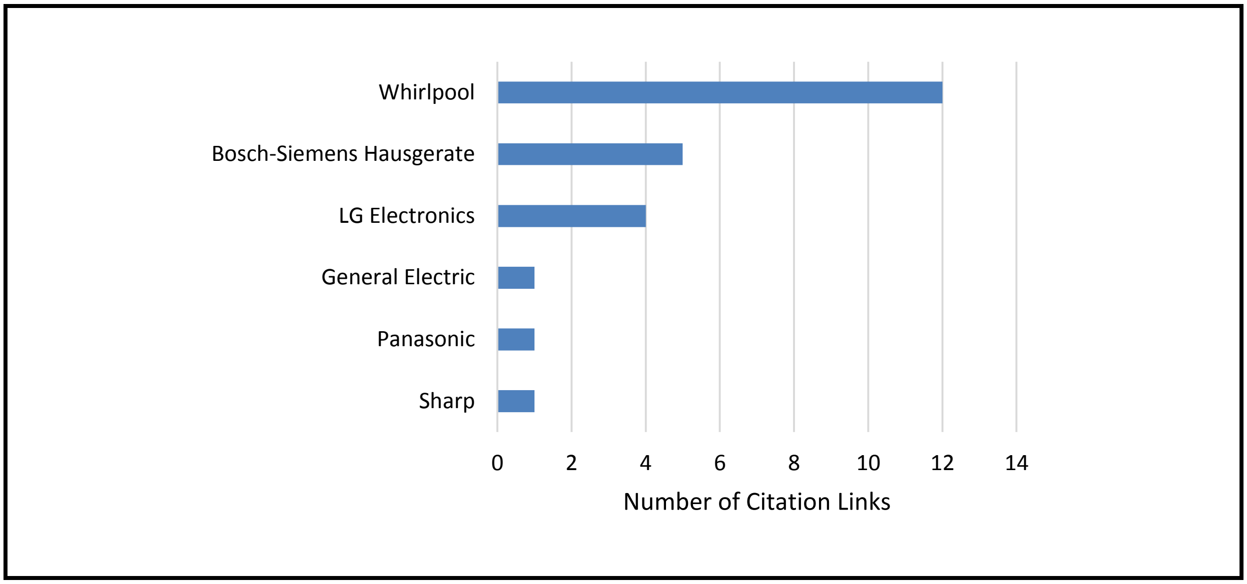
Figure 4-10. Average Number of Appliance Patent Families of Leading Companies and DOE Linked to the Appliance Patent Portfolios owned by Leading Organizations



.

While Figure 4-10 compares the impact of DOE (BTO) Appliances patents against the impact of patents owned by leading Appliances companies, Figure 4-11 counts the total number of citation links of patent families of leading companies to DOE (BTO). Whirlpool stands out when counting total citation links to DOE (BTO), but this count is relatively low, with a total of 19 links between Whirlpool and DOE. Not all patents have equal impact, and so these results should not be interpreted to mean DOE's small Appliances patent portfolio has not had a large impact on leading companies in this technology area. Indeed, as described below, several of the Whirlpool patents were identified as high-impact patents.

Figure 4-11. Total Number of Citation Links from Leading Companies' Appliance Patent Families to Earlier BTO-Appliance Patent Families



Note: Companies without citation links to BTO-Appliance families are omitted.

Table 4-10 shows the DOE-attributed Appliances patent families linked directly or indirectly to the largest number of subsequent patent families owned by leading companies in this technology. They are relatively older patents that have had a longer time period to become connected to subsequent generations of technology. Thus, the patent families in Table 4-10 represent older foundation technologies that are linked to subsequent developments made by leading companies in the Appliances industry.

The patent family at the head of Table 4-10 (with anchor patent[29] US #5032439) is assigned to MIT. It describes thermal insulation vacuum panels for use in refrigerators, and is linked to nine patent families assigned to leading Appliances patent families. These include Whirlpool patent families describing vacuum insulated cabinets for refrigerators, and General Electric and BSH patent families detailing vacuum panels for refrigerators. Also prominent in Table 4-10 are patent families describing microwave heating. These include Lockheed Martin families (anchor patents US #5521360 and US #5321222) related to variable frequency microwave heating, and a DOE

[29] The anchor patent for each patent family is a single patent from the family, generally the first patent issued, but it is not necessarily the priority filing (which may, for example, be a Japanese application).

patent family (anchor patent US #4996403) detailing control systems for microwave ovens.

Table 4-10. BTO-Appliances Patent Families Linked to the Most Appliance Patent Families of Leading Companies.

DOE Anchor Patent #	Application Date	Issue Date	Number of Linked Leading Company Families	Assignee	Title
5032439	25-08-89	7/16/1991	9	Massachusetts Inst of Technology	Thermal insulations using vacuum panels
5521360	9/14/1994	5/28/1996	5	Lockheed Martin Corp.	Apparatus and method for microwave processing of materials
4683154	19-08-85	7/28/1987	4	US Dept of Energy	Laser sealed vacuum insulation window
5321222	14-11-91	6/14/1994	3	Lockheed Martin Corp.	Variable frequency microwave furnace system
4996403	05-02-90	2/26/1991	3	US Dept of Energy	Acoustic emission feedback control for control of boiling in a microwave oven
4485638	22-02-83	12/4/1984	3	US Dept of Energy	Heat exchanger bypass system for an absorption refrigeration system

.

The backward tracing also identified high-impact Appliances patents owned by leading companies that have links back to BTO-attributed Appliances patents. Examples are US #7513132 assigned to Whirlpool, which describes a dry cleaning machine designed for domestic use. It has been cited by 17 subsequent patents since it was issued in 2009, which, based on its Citation Index is more than three times as many citations as expected given its age and technology. It is one of two high-impact Whirlpool patents related to dry-cleaning, the other being US #7739891. Whirlpool also has high-impact patents related to microwave cooking (US #6680467) and refrigerators designed for storing fruits and vegetables (US #7296422) that link to earlier BTO-Appliances patents. Panasonic has a high-impact patent (US #7316125) linked to the BTO Appliance set describing a recyclable insulation box for refrigerators.

4.8.5 Most Influential Attributed Patents

Table 4-11 lists highly cited BTO-Appliances patents. These are mainly older patents that have attracted large numbers of citations from subsequent generations of patents. There are also a few recent patents that have attracted more citations than expected given their relatively recent issue dates.

The patent at the head of Table 4-11 is US #5,521,360, assigned to Lockheed Martin, and describing variable frequency microwave heating. This patent was also noted as being among the BTO-Appliances patents with the most links to patent families owned by leading Appliances companies. Overall, it has been cited as prior art by 84 subsequent patents, and has a Citation Index of 5.61, which means that this is more than five times as many citations as expected given its age and technology. There is also another highly-cited Lockheed Martin patent related to microwave technology near the head of Table 4-11, namely US #5,321,222; Citation Count = 64; Citation Index = 3.77). Thus, it appears that the Appliances microwave research funded by BTO has formed part of the foundation for many subsequent technological developments.

Beyond these patents related to microwave technology, Table 4-11 is dominated by patents describing refrigeration, especially magnetic refrigeration. There are a series of patents assigned to DOE (e.g., US #4,332,135 and US #4,459,811) and to Astronautics Corp (e.g., US #4,408,463 and US #7,148,777) that describe magnetic refrigeration. These patents have all been cited more frequently than expected given their age and technology, especially the older foundational patents assigned to these organizations.

One other patent of note in Table 4-11 is US #4,683,154, granted in 1987 to DOE, and describing a laser sealed insulated window. It has been cited as prior art by 98 subsequent patents, which is more than any other of the BTO-Appliances patents. It is linked to subsequent innovations by the Guardian Industries and Corning outside the three targeted technology areas.

Table 4-11. Highly Cited BTO-attributed Appliance Patents Overall.

DOE Patent #	Application Date	Issue Date	Number of Citations Received	Citation Index	Assignee	Title
5521360	9/14/1994	5/28/1996	84	5.61	Lockheed Martin Corp.	Apparatus and method for microwave processing of materials
4683154	19-08-85	7/28/1987	98	4.79	US Dept of Energy	Laser sealed vacuum insulation window
4332135	27-01-81	6/1/1982	65	4.03	US Dept of Energy	Active magnetic regenerator
5321222	11/14/1991	6/14/1994	64	3.77	Lockheed Martin Corp.	Variable frequency microwave furnace system
4398398	14-08-81	8/16/1983	47	3.41	US Dept of Energy	Acoustical heat pumping engine
4107935	10-03-77	8/22/1978	49	3.39	US Dept of Energy	High temperature refrigerator
4408463	20-01-82	10/11/1983	42	2.84	Astronautics Corp	Wheel type magnetic refrigerator
5622055	3/22/1995	4/22/1997	33	2.37	Lockheed Martin Corp.	Liquid over-feeding refrigeration system and method with integrated accumulator-expander-heat exchanger
7148777	2/3/2005	12/12/2006	16	2.33	Astronautics Corp	Permanent magnet assembly
5689966	3/22/1996	11/25/1997	32	2.33	Battelle Memorial Institute	Method and apparatus for desuperheating refrigerant
5270092	8/8/1991	12/14/1993	43	2.29	University of California	Gas filled panel insulation
4459811	28-03-83	7/17/1984	28	1.86	US Dept of Energy	Magnetic refrigeration apparatus and method
5174130	3/14/1990	12/29/1992	27	1.78	Sonic Compressor Systems Inc	Refrigeration system having standing wave compressor
5032439	25-08-89	7/16/1991	28	1.55	Massachusetts Inst of Technology	Thermal insulations using vacuum panels
4542629	05-11-84	9/24/1985	20	1.48	US Dept of Energy	Variable effect desorber-resorber absorption cycle
7076959	3/7/2005	7/18/2006	9	1.44	Brookhaven Sci Associates	Enhanced magnetocaloric effect material

.

4.8.6 Summary of Findings

The patent analysis produced the following principal findings attributed to BTO's funding of Appliances R&D:

- A total of 67 Appliances patents attributed to BTO funding—comprised of 50 US patents, 6 EPO patents, and 11 WIPO patents--were grouped into 47 patent families.
- BTO-Appliances patent families with a priority date between 1981 and 1995 numbered 27, while only 11 families had a priority date from 2001 on, and none from 2011 on. This suggests that much of the innovative activity in Appliances technology associated with BTO R&D funding dates back more than a decade, with relatively little such activity in recent years—a pattern like that for HVAC patents attributed to BTO.
- Forward tracing revealed that BTO's Appliances patents are linked particularly extensively to subsequent patents classified as being related to Refrigeration Systems.
- Forward tracing also revealed a spillover influence of BTO's Appliances patents in the areas of Electric Heating, Layered Products (mainly composite materials) and Closures (such as doors and windows).
- Preparation for tracing backwards from the leading innovators in Appliances technology to the BTO patent set showed the BTO-appliance patent portfolio (47 families) to be dwarfed by those associated with the leading companies in the industry. BSH Hausgeräte has the largest Appliances patent portfolio (2,893 families), followed by LG Electronics (1,980), AB Electrolux (1,955), Whirlpool (1,798), Samsung (1,054), Koc Holding (821), Panasonic (766), Miele & Cie (553), General Electric (466), and Sharp, (290).
- The backward patent citation tracing revealed that BTO's 47 Appliances families are linked to 24 Appliances patent families owned by the leading companies, for an average of 0.51 linkages per BTO patent family. This average citation rate is much lower than Sharp's (4.21 links per family, not including self-citations), as well as General Electric's (4.15) -- putting BTO in last place when

ranked against the leading companies. At the same time, the BTO-Appliance family of patents is cited at a rate comparable to the two companies with the largest Appliances patent portfolios – BSH (0.60) and LG Electronics (0.81).

- The backward tracing also showed that among the leading companies, Whirlpool's Appliance patent families are linked particularly extensively to earlier BTO-Appliances patents, and the two areas where BTO-Appliances patents have had most of their influence on leading companies' patents are in vacuum insulated structures for refrigerators, and in microwave heating.
- None of the five companies found by forward tracing to have the most patent families linked to BTO's Appliances patents are among the 10 leading Appliances companies examined in the backward tracing, suggesting that much of the impact of DOE's Appliances patents has been on technological developments beyond those associated with the leading Appliances companies. In particular, the BTO-Appliance patents related to refrigeration and microwave heating appear to have had a notable influence on technologies outside the Appliance focus of this study.
- In terms of particularly influential BTO-appliance patents overall, two assigned to Lockheed Martin were identified as related to microwave technology.

5 Heat Pump Design Model and Alternative Refrigerants

This section describes BTO R&D related to the heat pump design model and alternative refrigerants research and presents estimates of benefits attributable to this R&D derived from estimated impacts on residential heat pump and central air conditioner energy performance trends.

5.1 TECHNOLOGY OVERVIEW

BTO has maintained an active program in alternative refrigerants research since 1981. Their research played an important role in transitioning toward more environmentally friendly fluids (first in terms of ozone depletion and more recently in terms of global warming potential) and improving the energy efficiency of all vapor compression systems—refrigerators, freezers, air conditioners for homes and automobiles, chillers, and heat pumps. A brief timeline of BTO activities follows:

- 1981-1992: Research in heat transfer characteristics, system performance, design and operability of zeotropic refrigerant mixtures at ORNL, NIST, and the University of Illinois.
- 1986-1991: Basic research on replacements for CFC refrigerants and insulation blowing agents.
- 1989-1997: Participation in Alternative Fluorocarbon Environmental Acceptability Study (AFEAS), testing alternatives to CFC refrigerants.
- 1991-1999: Participation in the Materials Compatibility and Lubricants Research (MCLR) program, researching

refrigerant and lubricant properties and related system design issues.

The 1987 Montreal Protocol limited the production and sale of CFC refrigerants and established a timetable for phasing out CFCs altogether. The Protocol was strengthened in 1990 and again in 1992, bringing forward the phase-out of CFCs in economically-developed countries to the end of 1995. The Clean Air Act Amendments of 1990 regulated the production and consumption of CFCs in the United States.[30]

The introduction of new refrigerants was to some extent at odds with improved efficiency. Some of the refrigerants were not inherently as efficient and implementing them meant that manufacturers lost decades of optimization experience and were forced to develop new technologies to achieve comparable efficiency with new refrigerants. BTO's research efforts focused on developing robust data on the characteristics of alternative refrigerants, which helped manufacturers to understand how to design and optimize new product lines which met environmental standards during the transitions from CFCs and HCFCs to HFCs, while maintaining and improving efficiencies.

An important tool for the design of vapor compression equipment—including and especially designing systems to work with new refrigerants—is the Heat Pump Design Model (HPDM). Oak Ridge National Laboratory (ORNL) developed the first version of the HPDM in the mid-1970s. A steady-state, vapor-compression equipment design tool, the HPDM has since been used by ORNL and industry (often in collaboration) to develop next-generation products. HPDM is a hardware-based model, which allows users to choose specific real world hardware as model inputs (e.g., heat exchangers, air flow control devices, and compressors) to run realistic simulations.

Like DOE's alternative refrigerants research, the HPDM cuts across all systems that utilize a vapor compression cycle. The HPDM played a role in transitioning to alternative refrigerants, particularly in modeling alternative system designs to accommodate the new fluids, then to optimize for them, leading to efficiency improvements.

The HPDM was expanded in 1988 to model variable-speed designs, and in 1995 to model non-chlorinated refrigerant

[30] The EPA provides details at http://www.epa.gov/ozone/title6/phaseout/

mixtures. These expansions paralleled industry's trend towards more advanced heat pumps and provided the optimization tools needed to maximize efficiency of increasingly complex systems. In addition to its use within ORNL, industry has adopted the model as well. Expert interviewees noted that, because HPDM software is distributed as open source, the core functionality of the HPDM provides a robust foundation upon which manufacturers can add feature sets and capabilities to tailor it to their research priorities.

Notably, ClimateMaster used the model in the design and development of the Trilogy 45 ground-coupled integrated heat pump, and NORDYNE used the model in the design and development of its iQ Drive compressor for air conditioners and heat pumps. Manufacturers also use HPDM to model the performance of new fluids that are being researched.

The HPDM was also included as part of the certification and compliance process for energy conservation standards air conditioners and heat pumps. The HPDM helped industry simulate the performance of its products and thereby lower the cost and reduce the time of product certification.

5.2 SAMPLE OF INTERVIEWEES

Table 5-1 summarizes the number of organizations contacted and interviewed, the number of persons contacted and interviewed, and our respective response rates; we interviewed 39 experts from 23 organizations.

To anticipate a concern, the source of contacts was not significantly correlated with attribution of impacts to BTO R&D, nor did we find correlations between BTO attribution and other respondent characteristics, including affiliation with a national laboratory, professional involvement in technical R&D efforts, and an index of their familiarity with specific BTO R&D activities. Respondents who had worked for a manufacturer (OEM, component, or fluid manufacturing company) tended to attribute lower impact to DOE. Despite this correlation, our main quantitative findings are fairly robust to a reweighting of responses more heavily toward industry. Section 9.2 provides details.

Table 5-1. Distribution of Experts Contacted and Interviewed

Stakeholder Group	Number of Organizations Contacted	Number of Organizations Represented in Interviews	Number of Individuals Contacted	Number of Interviews Conducted	Response Rate
Manufacturers	22	12	44	22	50%
Consulting	5	2	5	2	40%
University	13	3	13	4	31%
National Lab	1	1	8	6	75%
Industry/Trade Association	2	2	6	2	33%
Advocacy	2	1	2	1	50%
Other Government	3	2	8	4	50%
Total	47	23	84	39	46%

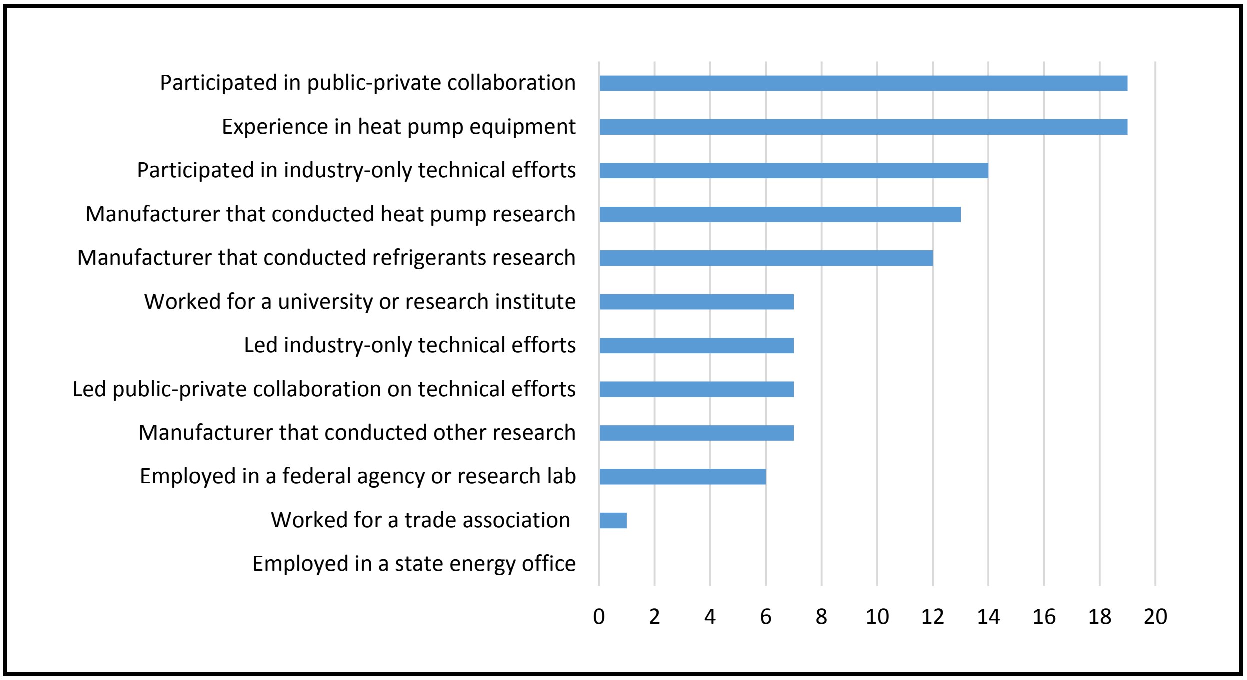
.

Of the individuals contacted, 39, or 46%, agreed to participate in an interview. Every effort was made to interview a diverse sample of experts to represent different perspectives on BTO's research investments. The group most heavily represented in the sample was private sector HVAC, heat pump, and refrigerant manufacturers (n=22). Interviewees from these companies were research engineers, R&D managers, product managers, and in one case, a legal counsel with experience in regulatory affairs.

Interviewee career experience is presented in Figure 5-1. The majority of respondents have experience participating in public-private collaborations and have worked on heat pump projects in some capacity.

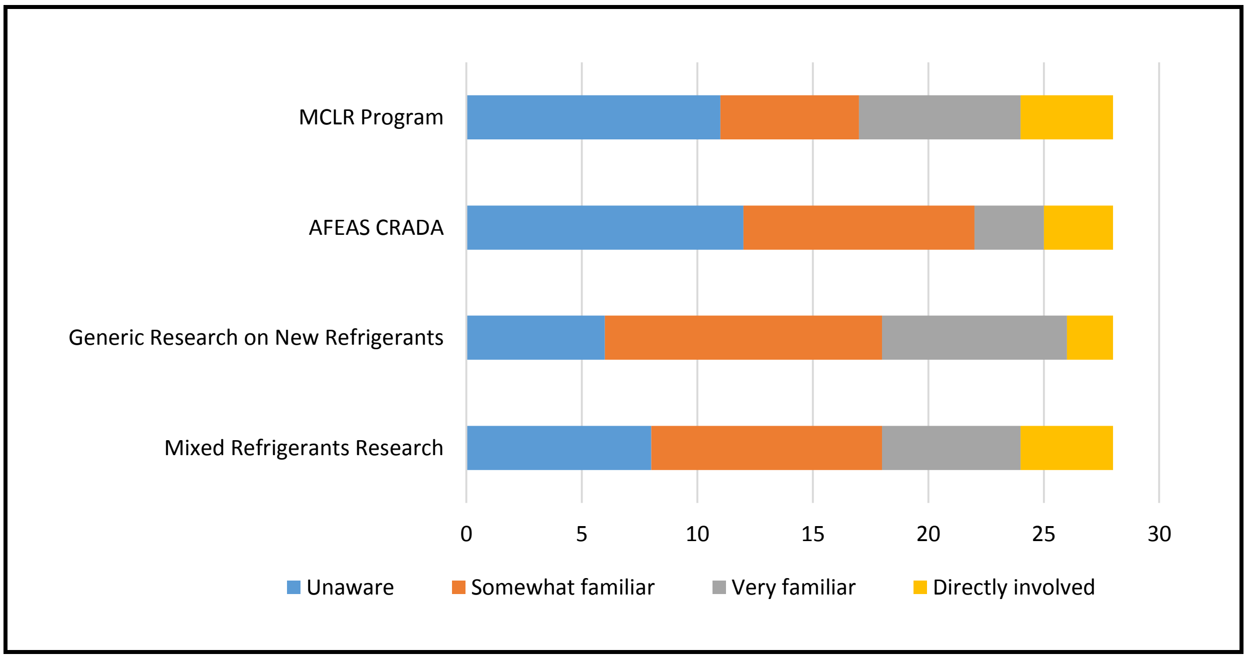
For the specific set of BTO R&D projects in this part of the evaluation, we asked respondents whether they were directly involved, very familiar, somewhat familiar, or unaware. Figure 5-2 summarizes their responses. More respondents were either very familiar with or directly involved in the MCLR program than any of the other activities, while the AFEAS CRADA was the least commonly known project to among experts in our sample.

Figure 5-1. Career Experience of Interviewees



Note: A single respondent can be included in multiple categories.

Figure 5-2. Interviewee Familiarity with Specific BTO Projects

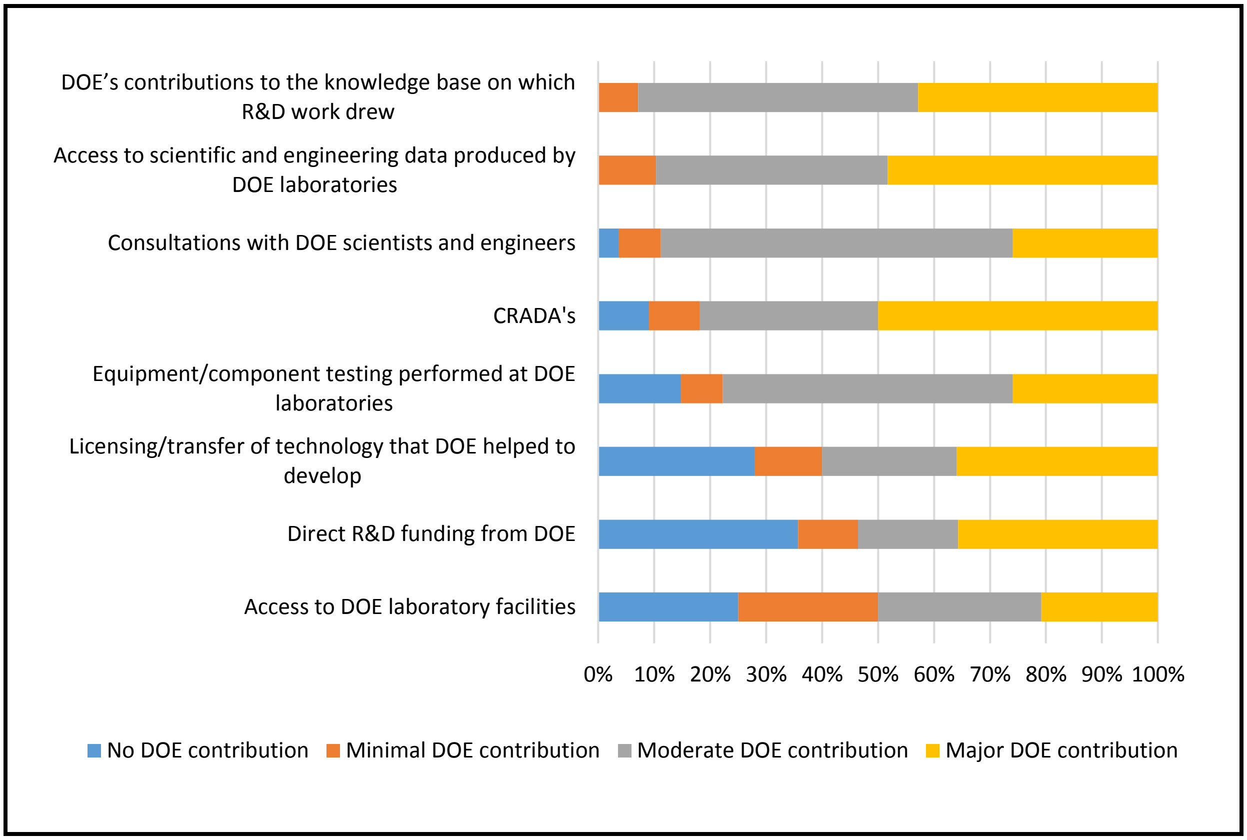


.

5.3 SUMMARY OF QUALITATIVE FINDINGS

Interviewees were asked how their R&D work was influenced by BTO research investments in the areas of heat pumps and alternative refrigerants. Experts in our sample rated DOE's contributions to the knowledge base and provision of scientific and engineering data as most significant. Figure 5-3 illustrates the range of opinions.

Figure 5-3. In what ways has private R&D (or your R&D work specifically) been influenced by BTO?



Note: Sorted in descending order by the combined percentage of "moderate" and "major" contribution.

Participants identified DOE's contribution to the knowledge base on which R&D work drew and access to DOE-generated data as its two most significant contributions to R&D in the HVAC sector. These factors include tools that DOE has developed and made available to the industry, including the Heat Pump Design Model (HPDM) and building efficiency models, which interviewees reported were regularly used and added significant value to private-sector research.

Interviewees also emphasized the importance of DOE's role as a trusted third party providing high quality data, independent of any company or companies.

In discussing alternative refrigerants, interviewees identified DOE as an important contributor of test facilities and data on fluid properties that proved valuable to managing the transition to new fluids. DOE's research into alternative refrigerants in the 1990s was regarded as having made for more efficient work and avoided duplication of effort. In the absence of DOE research, interviewees generally agreed that the transition to alternative refrigerants would still have been feasible, but would have been substantially more expensive and time-consuming for industry. DOE investments funded research on fluid properties that the entire industry needed and saved individual manufacturers from having to conduct the research independently.

Asked how BTO R&D influenced either the timing or levels of energy performance standards, only a few experts characterized the counterfactual in terms of a delay in the introduction of a new standard, although most thought it not unreasonable that new standards would have been delayed in the absence of BTO R&D. Most respondents thought that the standards would have been less stringent without BTO R&D and characterized the counterfactual trends in shipments-weighted energy performance accordingly. These results are discussed in greater detail in Sections 5.4 and 5.5.

5.4 SUMMARY OF QUANTITATIVE FINDINGS

Interviewees were asked to consider how BTO R&D influenced the evolution of average energy efficiency of residential heat pumps and central air conditioners. Using interviewee input, we developed counterfactual scenarios, describing how energy efficiency would have progressed in the absence of BTO R&D. Many interviewees were comfortable discussing how the energy performance trend for heat pumps and central air conditioners, depicted on the interview guide, would have been different without BTO R&D. These respondents described in words how the trend would have been different. If the conversation started this way, we referred back to this part of the discussion when we reached Question 15 in the interview guide (Appendix A), which asks whether average energy performance would have been different, and if so in what direction and by how much. In some cases, the interviews got to Question 15 first, and in those cases we would pivot from that question to the graph of the energy efficiency trend line. To have a practicable way to combine responses, we averaged answers to Question 15 and used that average (and a range around it, based on the variability of responses) to construct the counterfactual trendline in a formulaic way, described below. We compared the range of constructed trend lines with the counterfactual trends respondents described and were satisfied that by this procedure we were not losing any meaningful information.

Heat pumps and central air conditioners are rated according to their seasonal energy efficiency ratio (SEER), which indicates the relative amount of energy needed to provide a specific heating or cooling output. Specifically, SEER is the ratio of heating or cooling output to the amount of energy consumed. Thus, a higher SEER represents greater energy-efficiency.

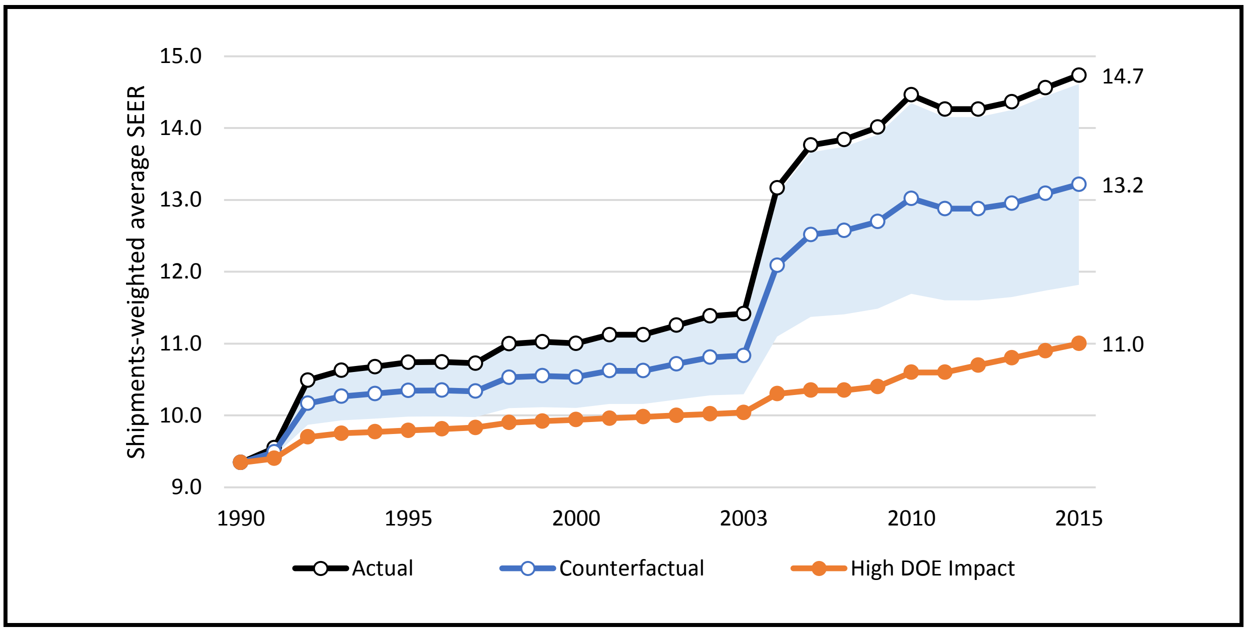
Heat pumps and central air conditioners are subject to the same minimum-SEER standards and their respective shipments-weighted average SEER levels move in lock-step, although heat pumps have slightly higher average SEER levels (the difference is less than 3%). For purposes of developing the counterfactual, we combined heat pumps and central air conditioners into one combined trendline for actual shipments-weighted average SEER, and we developed combined counterfactual trendlines to capture the DOE contribution.

Figure 5-4 illustrates the range of responses quantifying the relative DOE contribution to efficiency improvements. Some respondents expressed the opinion that the observed trend in shipments-weighted average SEER would not be any different without the DOE research. At the opposite end of the spectrum, some respondents believed that DOE research deserved credit for much if not all of the increase in shipments-weighted average SEER since 1990. This high-impact end of the range is represented by the orange trendline, which rises only to 11.0 SEER by 2015.

The impact attributed to DOE is represented by the difference between the actual and counterfactual trends. Thus, the level of impact attributed to DOE becomes greater as the counterfactual trend is displaced farther from the actual, reflecting a more gradual hypothesized improvement in average energy efficiency in the absence of DOE.

On average, responses put the counterfactual energy use at 13.2 SEER in 2015 (based on answers to Question 15 on the interview guide, Appendix A), shown by the blue trendline. This trendline was drawn as follows. First, we calculated the percentage of the increase that occurred from 1990 to 2015 that respondents attributed to DOE, based on a 2015 value of 13.2 SEER: (14.7 – 13.2)/(14.7 – 9.3) = 28%. Then, we applied the same 28% attribution to every year, attributing 28% of the difference between 9.3 SEER (the actual average SEER in 1990) and the actual average usage in each year to DOE. Thus, the attributable impact in 1990 is zero, and it increases gradually, reaching (14.7 – 13.2), or 28% of (14.7 – 9.3), in 2015. The shaded band around this trendline represents plus or minus one standard deviation of all 19 quantitative responses on which the 13.2 SEER average value is based (not all interviewees provided quantitative responses).

Figure 5-4. Shipments-Weighted Average SEER, Actual and Counterfactual (without DOE)



Notes: These are shipments-weighted averages, applying only to new air conditioners purchased in each year. The high scenario reflects the opinions of those interviewees who attributed the highest impact to DOE research. The actual trendline (Baxter et al., 2015) represents the opinions of those who attributed no impact to DOE research. In between these extremes, the middle scenario represents the average of all responses. The shaded band around it shows one standard deviation on either side.

The energy and resource benefits estimates developed in Section 5.5 are based on this average counterfactual trendline. The high and low bounds are based on the average, plus or minus 2.88 times the standard error (i.e., times the estimated standard deviation of the sample average), which yields a 99% confidence interval based on a *t* distribution with 18 degrees of freedom. The sample average of 13.2 SEER has an estimated standard deviation of 0.32 SEER (obtained by dividing the sample standard deviation, which is 1.4 SEER, by the square root of 19, which is the number of responses). This yields a 99% confidence interval of 12.3 SEER to 14.1 SEER in 2015. The confidence interval for the counterfactual in all other years is obtained in the same way as the average counterfactual, by holding constant the attributed percentage difference from 14.7 SEER.

5.5 ENERGY AND RESOURCE BENEFITS

This section develops estimates for the amount of energy saved, attributable to BTO R&D, based on the difference between actual and counterfactual trends summarized in Section 5.4. Estimates are developed in steps, explaining all assumptions, so that all calculations can be readily understood.

Step 1. First, the actual and counterfactual shipments-weighted average SEER in Figure 5-4 are converted into estimates of first-year energy savings. This is done by calculating the average energy saved by each new heat pump or central air conditioner and then multiplying by the number shipped in each year.

SEER is the ratio of heating or cooling output (measured in BTU/hour) to the amount of energy consumed (measured in watts), and its units are BTU/Wh. SEER is converted to energy savings based on the following simplifying assumptions:

1. Each heat pump heats or cools 108 million BTUs per year, consistent with a capacity of 36,000 BTU/hour operated for 3,000 hours each year.
2. Each central air conditioner cools 39.6 million BTUs per year, consistent with a capacity of 36,000 BTUs/hour operated for 1,100 hours each year.

These assumptions are based on average hours of operation (Energy Star, 2013) and average capacity (AHRI, 2017). Under these assumptions, annual energy consumption, in kWh, per heat pump or central air conditioner is given by the following formulas:

System	Average Energy Consumption (kWh) per Unit
Heat pump	$\frac{108{,}000{,}000 \text{ BTU}}{1{,}000 \times SEER}$
Central air conditioner	$\frac{39{,}600{,}000 \text{ BTU}}{1{,}000 \times SEER}$

Note: Because the units of SEER are BTU/Wh, 1,000 times SEER yields BTU/kWh, and dividing a number of BTUs by 1,000 times SEER yields kWh.

Therefore, annual energy savings, in kWh, per heat pump or central air conditioner is given by the following formulas:

System	Average Energy Savings (kWh) per Unit
Heat pump	$\frac{108{,}000 \text{ BTU}}{SEER_{C'Fact}} - \frac{108{,}000 \text{ BTU}}{SEER_{Actual}}$
Central air conditioner	$\frac{39{,}600 \text{ BTU}}{SEER_{C'Fact}} - \frac{39{,}600 \text{ BTU}}{SEER_{Actual}}$

Note: Actual SEER (part of which is attributed to DOE) is greater than counterfactual SEER (from which the DOE contribution is assumed away). Therefore, actual energy consumption is less than counterfactual energy consumption, and the savings attributed to DOE are obtained by subtracting the actual from the counterfactual.

The first-year savings for all heat pumps or central air conditioners shipped is therefore obtained by multiplying the average savings per unit by the number of units shipped.

Step 1 is summarized in Tables 5-2 and 5-3. Table 5-2 shows actual and counterfactual shipments-weighted average SEER (assumed to be the same for heat pumps and air conditioners) and the numbers of heat pumps and central air conditioners shipped. Table 5-3 shows the calculated first-year energy savings for heat pumps and central air conditioners.

Step 2. Next, the cumulative energy savings in each year are calculated by summing first-year energy savings (for both heat pumps and central air conditioners) over 15-year intervals. This calculation assumes that a heat pump or central air conditioner is operated for 15 years and that the attributed energy savings are the same in every year. For example, the total savings in 2000 will be equal to the sum of the first-year savings in 1986 (representing the savings attributable to heat pumps and central air conditioners purchased in 1986 that are being operated for their 15th and final year in 2000), in 1987 (representing the savings attributable to units purchased in 1987 and being operated for their 14th and penultimate year), in 1988, …, and in 2000.

Note that this calculation assumes that heat pumps and central air conditioners shipped in a given year were operated for that entire year, which will tend to overstate the savings. The overestimation is relatively small.

Step 3. Finally, cumulative energy savings are converted into energy cost savings by multiplying by the real price of electricity in each year.

Steps 2 and 3 are summarized in Table 5-4. Our estimates attribute savings to DOE of between 154 billion and 682 billion kWh and between $19 billion and $83 billion undiscounted dollars.

Table 5-2. Actual and Counterfactual Shipments-Weighted Average SEER, and Numbers of Heat Pumps and Central Air Conditioners Shipped

	Shipments-Weighted Average SEER, Actual and Counterfactual				Shipments (thousands)	
Year	**Actual**	**Low DOE Impact**	**Mid DOE Impact**	**High DOE Impact**	**Heat Pumps**	**CACs**
1990	9.3	9.3	9.3	9.3	809	2,920
1991	9.5	9.5	9.5	9.5	764	3,006
1992	10.5	10.4	10.2	10.0	799	2,914
1993	10.6	10.5	10.3	10.0	882	3,188
1994	10.7	10.5	10.3	10.1	1,008	3,888
1995	10.7	10.6	10.3	10.1	1,025	4,063
1996	10.7	10.6	10.3	10.1	1,148	4,523
1997	10.7	10.6	10.3	10.1	1,131	4,229
1998	11.0	10.8	10.5	10.2	1,260	4,980
1999	11.0	10.8	10.6	10.3	1,293	5,354
2000	11.0	10.8	10.5	10.3	1,339	5,346
2001	11.1	10.9	10.6	10.3	1,442	4,835
2002	11.1	10.9	10.6	10.3	1,484	5,263
2003	11.3	11.0	10.7	10.4	1,626	5,181
2004	11.4	11.2	10.8	10.5	1,886	5,515
2005	11.4	11.2	10.8	10.5	2,137	6,471
2006	13.2	12.7	12.1	11.4	2,118	4,951
2007	13.8	13.3	12.5	11.8	1,903	4,456
2008	13.8	13.3	12.6	11.8	1,865	3,968
2009	14.0	13.5	12.7	11.9	1,642	3,516
2010	14.5	13.9	13.0	12.1	1,748	3,420
2011	14.3	13.7	12.9	12.0	1,765	3,745
2012	14.3	13.7	12.9	12.0	1,698	3,916
2013	14.4	13.8	12.9	12.1	1,969	4,201
2014	14.6	14.0	13.1	12.2	2,354	4,500
2015	14.7	14.1	13.2	12.3	2,269	4,546

Notes: CACs = central air conditioners. Shipments data from AHRI (2017).

Table 5-3. First-Year Energy Savings for Heat Pumps and Central Air Conditioners (GWh)

	Heat Pumps			Central Air Conditioners		
Year	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
1990	0	0	0	0	0	0
1991	20	52	85	30	76	122
1992	101	262	429	135	350	573
1993	121	316	519	161	418	687
1994	143	372	612	202	526	866
1995	150	392	645	218	569	937
1996	169	440	725	244	636	1,047
1997	165	429	706	226	588	968
1998	209	547	903	303	793	1,310
1999	217	569	940	330	863	1,427
2000	223	583	964	326	854	1,411
2001	252	661	1,094	310	813	1,345
2002	259	680	1,126	337	885	1,464
2003	299	784	1,301	349	916	1,519
2004	362	952	1,581	388	1,021	1,695
2005	414	1,090	1,812	460	1,211	2,012
2006	576	1,548	2,632	494	1,327	2,255
2007	549	1,485	2,541	472	1,275	2,182
2008	542	1,467	2,512	423	1,144	1,959
2009	484	1,311	2,249	380	1,029	1,766
2010	532	1,446	2,492	381	1,037	1,787
2011	530	1,439	2,475	412	1,119	1,925
2012	510	1,384	2,380	431	1,170	2,013
2013	595	1,617	2,784	466	1,265	2,178
2014	720	1,960	3,382	505	1,374	2,370
2015	701	1,912	3,304	515	1,404	2,427

Notes: First-year energy savings is obtained by multiplying the number of heat pumps or central air conditioners shipped by the average energy savings per unit, calculated from the actual and counterfactual SEER using the formula given above. 1 GWh = 1,000,000 kWh.

Table 5-4. Cumulative Energy and Energy Cost Savings

Year	Low Energy Savings (GWh)	Mid Energy Savings (GWh)	High Energy Savings (GWh)	Real Price (2015 dollars /GWh)	Low Cost Savings (Millions of 2015 dollars)	Mid Cost Savings (Millions of 2015 dollars)	High Savings (Millions of 2015 dollars)
1990	0	0	0	142,025	0	0	0
1991	50	128	207	139,934	7	18	29
1992	285	739	1,209	138,676	40	103	168
1993	567	1,473	2,414	136,480	77	201	329
1994	912	2,372	3,892	133,987	122	318	521
1995	1,281	3,333	5,474	130,642	167	435	715
1996	1,694	4,410	7,245	126,310	214	557	915
1997	2,084	5,427	8,920	124,458	259	675	1,110
1998	2,596	6,767	11,133	120,091	312	813	1,337
1999	3,143	8,199	13,500	116,091	365	952	1,567
2000	3,693	9,637	15,875	113,411	419	1,093	1,800
2001	4,255	11,111	18,314	114,855	489	1,276	2,103
2002	4,852	12,676	20,904	111,206	540	1,410	2,325
2003	5,499	14,376	23,724	112,315	618	1,615	2,665
2004	6,249	16,348	27,001	112,282	702	1,836	3,032
2005	7,123	18,649	30,825	114,694	817	2,139	3,535
2006	8,143	21,396	35,505	122,285	996	2,616	4,342
2007	8,929	23,545	39,225	121,730	1,087	2,866	4,775
2008	9,613	25,422	42,491	123,973	1,192	3,152	5,268
2009	10,132	26,864	45,028	127,132	1,288	3,415	5,725
2010	10,676	28,385	47,725	125,411	1,339	3,560	5,985
2011	11,205	29,866	50,353	123,490	1,384	3,688	6,218
2012	11,755	31,403	53,072	122,628	1,442	3,851	6,508
2013	12,304	32,945	55,822	123,399	1,518	4,065	6,888
2014	12,982	34,847	59,207	125,348	1,627	4,368	7,421
2015	13,649	36,725	62,563	126,700	1,729	4,653	7,927
Total	153,671	407,046	681,628		18,748	49,675	83,209

Notes: Nominal energy prices are "Average Retail Price of Electricity, Residential" (dollars per kWh, including taxes) from the U.S. Energy Information Administration. Nominal prices are converted to constant 2015 dollars using the Consumer Price Index for All Urban Consumers: All Items, Annual, Seasonally Adjusted.

5.6 ENVIRONMENTAL HEALTH BENEFITS

This section develops estimates for the numbers of avoided adverse health events associated with the estimates of energy savings developed in Section 5.5. Estimates are again developed in steps, explaining all assumptions, so that all calculations can be readily understood. Unless otherwise noted, all assumptions described in this section come directly from the COBRA model, an overview of which is provided in Section 2.2.

Step 1. First, the energy savings for each year, given in Table 5-4, are transformed into amounts of criteria pollutants abated. This is done by applying the multipliers in Table 5-5, which are specific to the year in which the electricity was generated.

Tables 5-6 and 5-7 show the total amounts of these pollutants abated, based on low, middle, and high impact scenarios.

Table 5-5. Average Amounts of Criteria Pollutants Released from Fuel Combustion by Electric Utilities in the United States (tons per GWh)

Year	PM 2.5	SO2	NOx	NH3	VOC
1990	0.0398	5.2370	2.1933	0.0000	0.0155
1991	0.0342	5.1350	2.1208	0.0000	0.0143
1992	0.0344	4.9989	2.1090	0.0000	0.0143
1993	0.0350	4.7507	2.0803	0.0000	0.0141
1994	0.0333	4.5847	2.0215	0.0000	0.0139
1995	0.0319	3.6022	1.9037	0.0000	0.0131
1996	0.0455	3.7069	1.7897	0.0017	0.0144
1997	0.0460	3.7785	1.7973	0.0017	0.0150
1998	0.0359	3.7058	1.7215	0.0022	0.0156
1999	0.1681	3.4057	1.5484	0.0030	0.0146
2000	0.1545	2.9973	1.4019	0.0029	0.0163
2001	0.1563	2.9038	1.3159	0.0029	0.0162
2002	0.1312	2.7047	1.2205	0.0075	0.0128
2003	0.1312	2.6635	1.1175	0.0072	0.0127
2004	0.1291	2.5814	0.9997	0.0067	0.0123
2005	0.1272	2.5655	0.9351	0.0063	0.0119
2006	0.1101	2.3484	0.8827	0.0065	0.0115
2007	0.0913	2.0898	0.8139	0.0066	0.0109
2008	0.0751	1.8916	0.7631	0.0068	0.0106
2009	0.0695	1.7118	0.7134	0.0069	0.0108
2010	0.0582	1.3809	0.5958	0.0064	0.0101
2011	0.0501	1.1281	0.5098	0.0062	0.0099
2012	0.0484	1.1423	0.4854	0.0062	0.0098
2013	0.0459	1.1369	0.4524	0.0062	0.0095
2014	0.0433	0.7876	0.4187	0.0062	0.0091
2015	0.0435	0.5518	0.3578	0.0063	0.0092

Notes: Quantities of pollutants are drawn from EPA (2017b). U.S. electric utility outputs are drawn from EIA (2017c).

Table 5-6. BTO-Attributed PM 2.5, NH3, and VOC Abated (tons)

	PM2.5			NH3			VOC		
Year	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
1990	0	0	0	0	0	0	0	0	0
1991	2	4	7	0	0	0	1	2	3
1992	10	25	42	0	0	0	4	11	17
1993	20	52	85	0	0	0	8	21	34
1994	30	79	129	0	0	0	13	33	54
1995	41	106	175	0	0	0	17	44	72
1996	77	201	330	3	8	13	24	64	105
1997	96	250	411	4	9	15	31	81	133
1998	93	243	399	6	15	25	40	105	173
1999	528	1,379	2,270	9	24	40	46	120	198
2000	571	1,489	2,453	11	28	46	60	157	258
2001	665	1,737	2,862	13	33	54	69	180	297
2002	636	1,663	2,742	36	95	156	62	162	268
2003	721	1,886	3,112	39	103	170	70	182	301
2004	807	2,110	3,485	42	110	181	77	200	331
2005	906	2,371	3,920	45	117	194	85	222	366
2006	897	2,356	3,909	53	139	230	94	246	409
2007	815	2,149	3,580	59	155	258	98	257	429
2008	722	1,909	3,191	66	174	291	102	269	450
2009	704	1,868	3,130	70	185	310	109	290	486
2010	621	1,651	2,776	68	181	304	108	286	481
2011	561	1,495	2,521	69	184	310	111	296	498
2012	569	1,520	2,569	73	196	331	115	306	518
2013	565	1,512	2,562	77	205	347	116	311	528
2014	562	1,510	2,565	81	217	369	118	318	540
2015	594	1,597	2,721	85	230	391	125	336	573
Total	11,813	31,161	51,946	907	2,407	4,036	1,702	4,500	7,521

.

Table 5-7. BTO-Attributed SO2 and NOx (tons)

	SO2			NOx		
Year	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
1990	0	0	0	0	0	0
1991	257	657	1,060	106	271	438
1992	1,427	3,696	6,042	602	1,559	2,549
1993	2,695	6,999	11,469	1,180	3,065	5,022
1994	4,183	10,875	17,843	1,844	4,795	7,868
1995	4,615	12,007	19,718	2,439	6,345	10,420
1996	6,279	16,346	26,858	3,032	7,892	12,967
1997	7,875	20,507	33,703	3,746	9,754	16,031
1998	9,621	25,077	41,256	4,469	11,649	19,165
1999	10,705	27,925	45,977	4,867	12,696	20,904
2000	11,068	28,884	47,582	5,177	13,510	22,255
2001	12,355	32,263	53,181	5,599	14,621	24,101
2002	13,122	34,284	56,540	5,922	15,471	25,514
2003	14,647	38,291	63,190	6,146	16,066	26,513
2004	16,131	42,203	69,701	6,247	16,343	26,992
2005	18,275	47,845	79,083	6,661	17,439	28,825
2006	19,124	50,248	83,380	7,188	18,886	31,339
2007	18,661	49,205	81,974	7,268	19,164	31,926
2008	18,183	48,088	80,375	7,336	19,400	32,426
2009	17,343	45,985	77,078	7,228	19,164	32,123
2010	14,742	39,196	65,903	6,360	16,911	28,433
2011	12,640	33,692	56,803	5,712	15,225	25,668
2012	13,429	35,873	60,626	5,706	15,243	25,761
2013	13,988	37,454	63,462	5,566	14,904	25,252
2014	10,224	27,445	46,631	5,435	14,590	24,790
2015	7,531	20,265	34,521	4,884	13,142	22,388
Total	279,120	735,310	1,223,956	120,718	318,106	529,669

.

Step 2. Next, these amounts of abated pollutants are transformed into numbers of avoided adverse health outcomes, and associated dollar values, based on the assumptions of the COBRA model. Table 5-8 summarizes these assumptions, based on 2017 emissions (as will be explained, a population deflator is used to develop comparable numbers for all other years).

Table 5-8. COBRA parameters for Electric Utility Fuel Combustion (rounded)

	Number of events avoided per 1000 tons of pollutant abated					Assumed Monetary Value (2015 dollars)		
Adverse Health Event	PM 2.5	SO2	NOx	NH3	VOC	3%	7%	Undiscounted
Adult Mortality (low)	8.8	3.3	0.8	1.3	0.1	8,434,924	7,512,853	9,126,478
Adult Mortality (high)	19.9	7.6	1.8	3.0	0.2	8,434,924	7,512,853	9,126,478
Infant Mortality	0.02	0.01	0.00	0.00	0.00	9,401,680	9,401,680	9,401,680
Non-fatal Heart Attacks (low)	1.1	0.4	0.1	0.2	0.01	122,181	118,759	124,748
Non-fatal Heart Attacks (high)	10.0	3.9	0.9	1.4	0.1	122,181	118,759	124,748
Resp. Hosp. Adm.	2.6	1.0	0.2	0.3	0.03	25,663	25,663	25,663
CVD Hosp. Adm.	3.2	1.2	0.3	0.4	0.04	38,860	38,860	38,860
Acute Bronchitis	12.8	4.8	1.2	2.1	0.2	477	477	477
Upper Res. Symptoms	232.7	87.6	21.0	38.8	3.0	33	33	33
Lower Res. Symptoms	162.9	61.3	14.7	27.2	2.1	21	21	21
Asthma ER Visits	5.1	1.8	0.4	0.7	0.1	426	426	426
MRAD	6,610	2,462	581	1,186	82.4	68	68	68
Work Loss Days	1,109	412.5	97.4	199.9	13.8	160	160	160
Asthma Exacerbations	246.2	92.7	22.2	41.4	3.1	57	57	57

Notes: Parameters have been rounded. Undiscounted monetary values are approximated based on simple linear extrapolation from the 3% and 7% values. MRAD = minor restricted activity day.

Step 3. Finally, the parameters in Table 5-8 are applied to the attributed abatements in Tables 5-6 and 5-7 to obtain estimates of attributed avoided adverse health events and associated values in each year. Because the parameters in Table 5-8 are based on the United States' population in 2017, a simple population deflator is applied to each year: the ratio of the U.S. population in the given year to the U.S. population in 2017. Table 5-9 reports the estimated value of all avoided adverse health events at between $10 billion and $95 billion, without discounting.

Table 5-9. Value of All BTO-Attributed Avoided Adverse Health Events

	Value based on low numbers of adult mortality and non-fatal heart attacks (millions of 2015 dollars)			Value based on high numbers of adult mortality and non-fatal heart attacks (millions of 2015 dollars)		
Year	Low	Middle	High	Low	Middle	High
1990	0	0	0	0	0	0
1991	7	18	28	16	40	64
1992	39	101	165	88	228	373
1993	75	194	318	169	439	720
1994	117	305	501	266	691	1,134
1995	134	349	573	303	789	1,296
1996	184	480	788	417	1,086	1,784
1997	234	608	999	528	1,376	2,261
1998	286	746	1,228	648	1,689	2,778
1999	351	916	1,509	795	2,073	3,414
2000	370	965	1,590	837	2,184	3,597
2001	418	1,091	1,799	946	2,470	4,071
2002	443	1,158	1,910	1,003	2,621	4,322
2003	497	1,300	2,146	1,125	2,942	4,855
2004	550	1,440	2,378	1,245	3,257	5,380
2005	626	1,638	2,708	1,416	3,708	6,128
2006	659	1,731	2,872	1,491	3,917	6,500
2007	646	1,705	2,840	1,463	3,857	6,426
2008	632	1,672	2,794	1,430	3,783	6,323
2009	611	1,620	2,716	1,383	3,666	6,145
2010	527	1,401	2,355	1,192	3,169	5,328
2011	459	1,224	2,063	1,039	2,769	4,668
2012	487	1,300	2,197	1,101	2,942	4,972
2013	506	1,354	2,294	1,144	3,063	5,191
2014	394	1,058	1,797	892	2,394	4,067
2015	313	843	1,436	709	1,908	3,250
Total	9,566	25,216	42,004	21,646	57,060	95,046

Notes: Attributed avoided mortalities based amounts of pollutants abated and COBRA model parameters. Within each block of three columns, Low/Middle/High refers to the scenarios in Tables 5-5 and 5-6. Lower values in the left block of Low/Middle/High scenarios are based on low numbers of adult mortality and non-fatal heart attacks in Table 5-7; higher values in the right block are based on high numbers for adult mortality and non-fatal heart attacks. Each year's estimates are deflated by the ratio of the U.S. population in the given year to the U.S. population in 2017. Totals are not discounted.

5.7 ENERGY SECURITY BENEFITS

DOE-attributed energy savings (Table 5-4) are associated with between 2 million and 10 million avoided barrels of imported crude oil (Table 5-10). The approach used to convert fuel savings into avoided crude imports is described in Section 2.5.

Table 5-10. BTO-Attributed Avoided Crude Oil Imports: Heat Pumps and Central Air Conditioners

Year	Percentage of U.S. Crude Oil Supply Imported	Petroleum Consumed for Electricity Generation (thousands of barrels)	Total Electricity Generation (GWh)	Avoided Crude Oil Imports (thousands of barrels)		
				Low	Middle	High
1990	44.0%	218,800	3,037,827	0	0	0
1991	43.5%	203,669	3,073,799	1	3	6
1992	45.4%	172,241	3,083,882	7	17	29
1993	49.9%	192,462	3,197,191	16	41	68
1994	50.9%	183,618	3,247,522	25	64	105
1995	51.7%	132,578	3,353,487	24	64	104
1996	52.9%	144,626	3,444,188	35	91	150
1997	56.1%	159,715	3,492,172	50	130	214
1998	58.5%	222,640	3,620,295	87	227	374
1999	59.0%	207,871	3,694,810	97	254	418
2000	60.2%	195,228	3,802,105	107	278	458
2001	61.7%	216,672	3,736,644	142	371	611
2002	61.2%	168,597	3,858,452	121	316	521
2003	63.2%	206,653	3,883,185	173	451	744
2004	65.2%	203,494	3,970,555	195	510	842
2005	66.5%	206,785	4,055,423	226	590	976
2006	66.4%	110,634	4,064,702	137	361	599
2007	66.2%	112,615	4,156,745	149	394	656
2008	66.8%	80,932	4,119,388	118	311	520
2009	62.9%	67,668	3,950,331	102	270	453
2010	62.6%	65,071	4,125,060	98	262	440
2011	60.3%	52,387	4,100,141	81	215	362
2012	56.8%	40,977	4,047,765	63	169	285
2013	50.5%	47,492	4,065,964	68	181	307
2014	46.3%	53,593	4,093,606	74	197	335
2015	45.5%	49,145	4,077,601	70	188	320
Total				2,264	5,956	9,897

Notes: Avoided barrels of imported crude in a given year are obtained by taking the product of (1) the percentage of U.S. crude oil supply imported, (2) the number of barrels of petroleum liquids consumed in electricity generation, and (3) the percentage reduction in electricity consumption attributed to DOE, and then multiplying by 42/45 (to convert barrels of refined petroleum liquids to barrels of crude). A detailed explanation is provided in Section 2.5. Percentage savings is calculated by dividing DOE-attributed savings (Table 5-4) by U.S. electric utility outputs (EIA, 2017c).

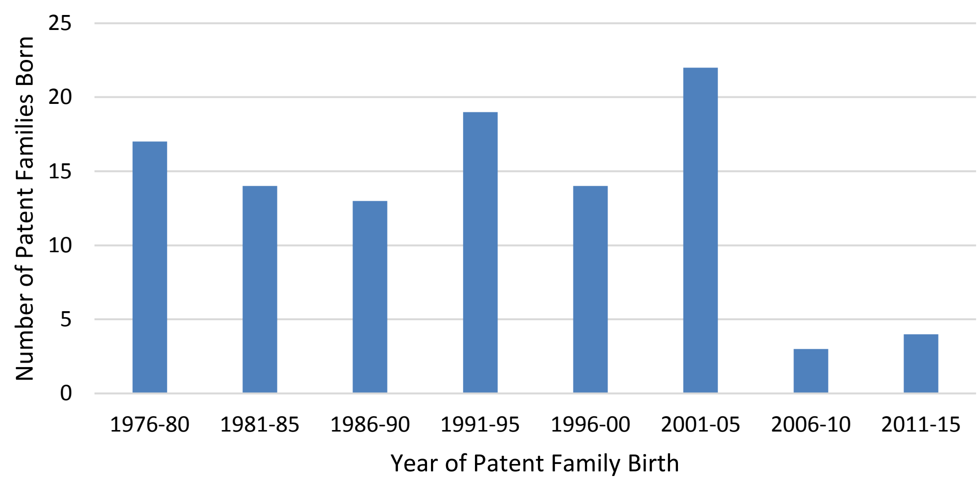
5.8 KNOWLEDGE BENEFITS

This section assesses selected knowledge benefits resulting from BTO's funding of R&D in HVAC technologies, including but not limited to residential heat pumps and central air conditioners.

5.8.1 Trends in Attributed Patenting

Figure 5-5 shows the number of BTO-attributed HVAC patent families by priority year, which is the year of the first application in each patent family, and in that sense it is the year in which the patent family was "born." Between 1976 and 2005, the number of BTO-HVAC patent family births fluctuated between 13 and 22, but since 2005, the number has declined. In 2006-2010, only three patent families were born, followed by four in 2011-2015. The decline presumably reflects a shift in BTO investments away from HVAC toward other technology areas.

Figure 5-5. Trend in BTO-Attributed HVAC Patent Family Births



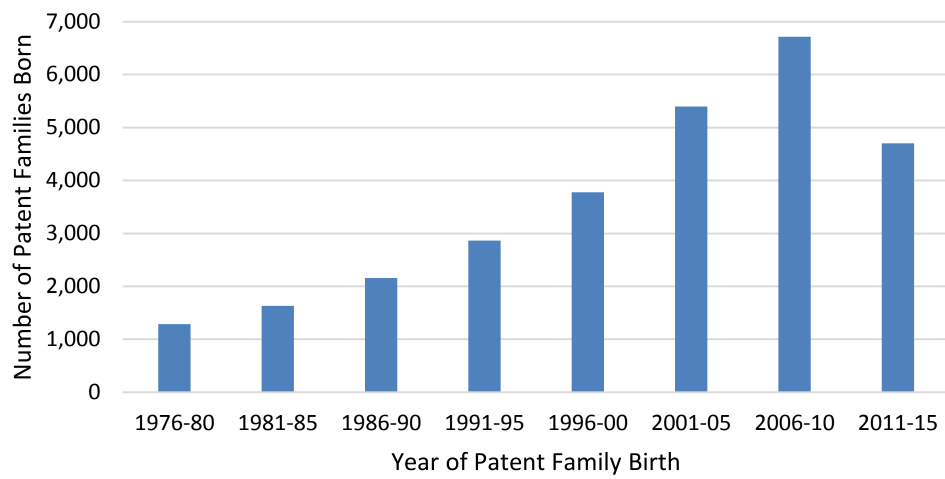
Note: Patent families are assigned to the year of the first patent application in the family.

The number of HVAC patent family births springing from all organizations has steadily increased over the same period (Figure 5-6).[31]

A comparison of the patterns in Figures 6-1 and 6-2 suggests that in tracing the influence of BTO-attributed HVAC patents, it is the impact of older, possibly foundational, technologies resulting from BTO R&D funding that is seen rather than the impact of more recent innovations. This interpretation is consistent with BTO's mission of supporting early stage R&D which can be leveraged by all industry stakeholders to improve the efficiency of follow-on R&D and eventual product offerings.

[31] The number of patent family births in 2011-2015 is biased downward by time lags in the patenting process; most patent families filed in 2015, and possibly in 2014, had not yet been issued when this analysis was carried out.

Figure 5-6. Trend in All HVAC Patent Family Births



Note: Patent families are assigned to the year of the first patent application in the family.

5.8.2 Assignees of Attributed Patents

DOE is the most prolific assignee with 20 patent families, followed by DOE lab managers Lockheed Martin (9 families), UT-Battelle (7 families), and Midwest Research Institute (6 families). The next three assignees are all companies, namely Phillips Engineering (5 families), Westinghouse (5) and Consolidated Natural Gas (4). The University of California, Climate Master, Gas Technology Institute, AIL Research, and Battelle Memorial Institution each are assigned several of the patents.

DOE has funded research carried out in its own labs and, to a lesser extent, at commercial organizations. However, it was not found to have funded extensive HVAC research at any of the top companies identified as leading in downstream HVAC innovation. One reason this is not especially surprising is that only two of the leading companies are based in the United States.

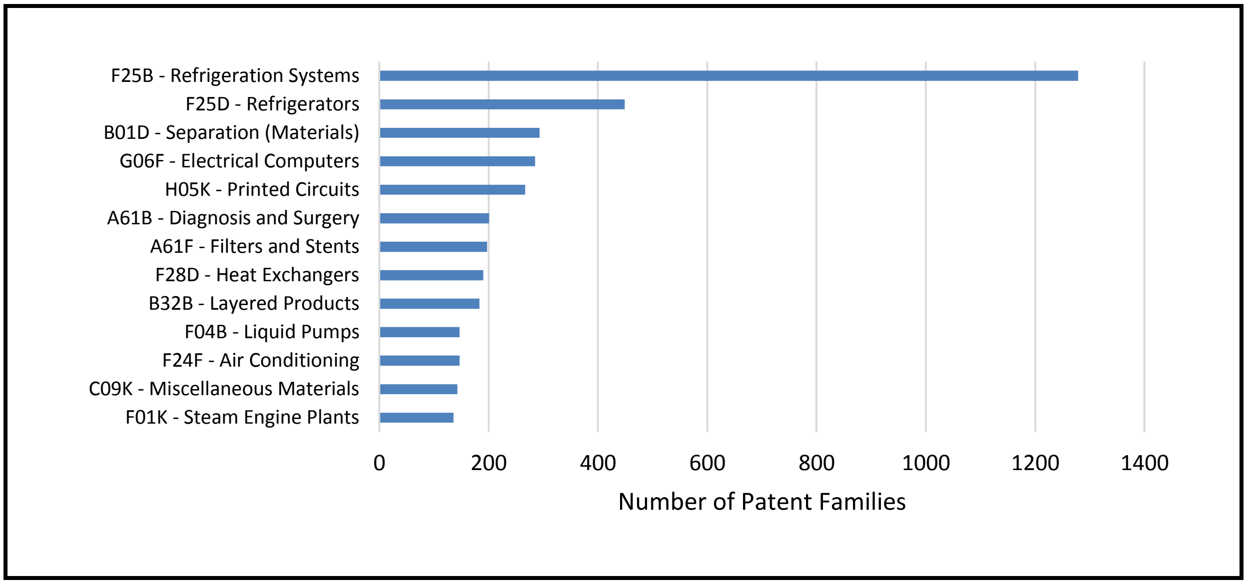
5.8.3 Influence of Attributed Patents: Forward Tracing

Forward tracing of BTO-HVAC patents shows the influence of BTO-funded HVAC research both on the HVAC industry and on other areas of technology, thereby revealing the breadth of influence of the HVAC research funded by BTO. This analysis is facilitated by identification of the primary International Patent

Classifications (IPCs) of the patent families linked directly and indirectly to the earlier BTO-HVAC patent families.[32]

Figure 5-7 shows the patents by their 4-digit IPCs that are linked to BTO-HVAC patents through two generations of forward citations. Refrigeration Systems (IPC F25B) is dominant, followed by Refrigerators (IPC F25D). Adding the second level of citations increases the prominence of certain other IPCs – notably Electrical Computers (G06F) and Printed Circuits (H05K). Most of the patents in these IPCs that are linked to earlier BTO-HVAC patents describing cooling systems for electronics and integrated circuits.

Figure 5-7. Patent Families Linked to BTO-Attributed Prior HVAC Patents by IPC



Note: IPC = International Patent Classification.

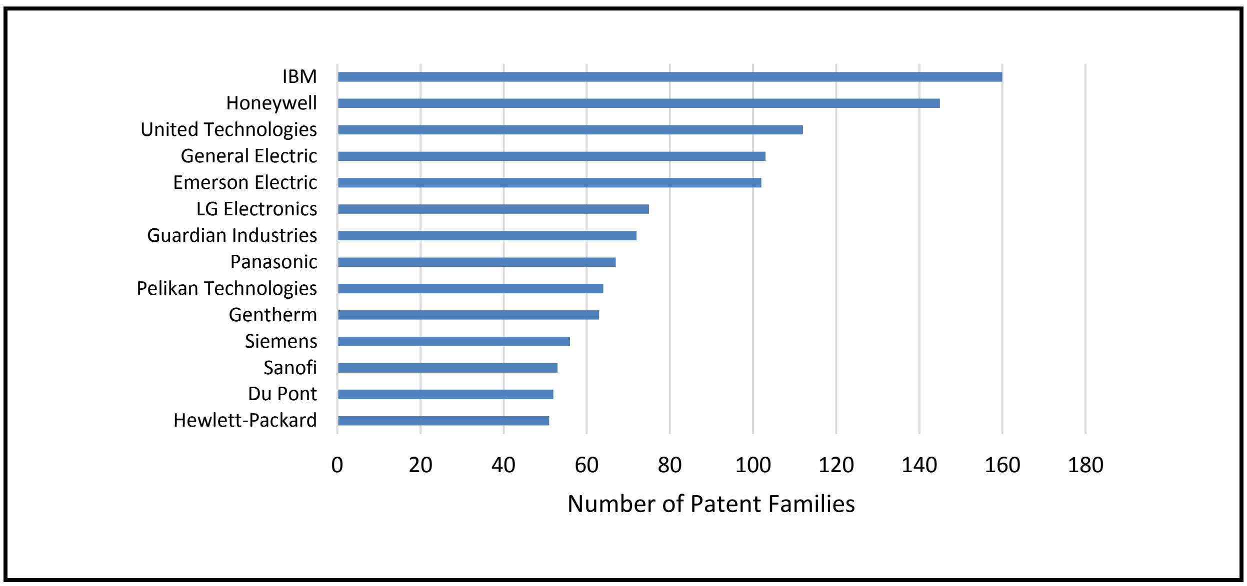
The organizations with the largest number of patent families linked directly or indirectly to the earlier BTO-HVAC patents are shown in Figure 5-8. This figure is derived by taking into account all patent families—not just HVAC technology—assigned to all organizations. It reveals that IBM has the most families (160) linked to the earlier set of BTO-HVAC patents. These IBM patent families describe a variety of technologies, notably cooling systems for electronics racks and printed

[32] In some cases, different patent documents within a patent family may have different first IPCs, although it is unusual for the IPCs to differ at the 4-digit level used here. To simplify the analysis, we used the primary IPC from the anchor patent in each patent family.

circuits, fans for computers, and methods for monitoring air quality. This is an example of how, over just two generations of patent links, the influence of patents can extend substantially beyond their immediate targeted field of technology.

Following IBM in Figure 5-8 are two of the top-ten companies in HVAC patenting–Honeywell and United Technologies. Next there are two large multinationals–General Electric and Emerson Electric. GE's patents that are linked to the BTO-HVAC patents describe cooling systems, and also technologies associated with combustion engines and turbines. Meanwhile, Emerson's patents that are linked to the BTO-HVAC set describe various aspects of climate control, including refrigerants, heat exchangers and compressors. The results suggest that DOE's HVAC patents have influenced both technologies developed by leading HVAC companies, and the technologies of other organizations.

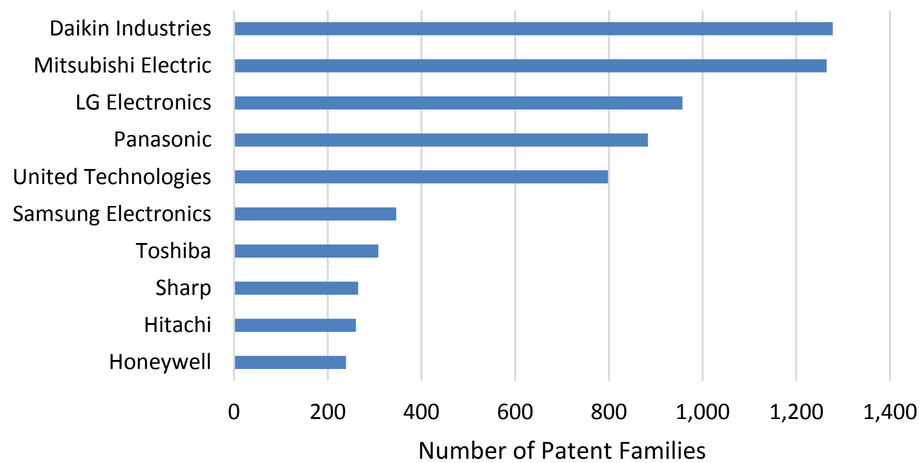
Figure 5-8. Organizations with the Greatest Numbers of Patent Families Linked to BTO-Attributed Prior HVAC Patents by IPC



5.8.4 Influence of Attributed Patents: Backward Tracing

The 10 companies with the largest number of HVAC patent families as revealed by a recent patent search are shown in Figure 5-9. This includes patent families associated with all variant names under which the companies have patents, including all subsidiary names. The HVAC patent families of these ten companies form the starting point of the backward tracing in this technology area.

Figure 5-9. Companies with the Ten Largest HVAC Patent Portfolios

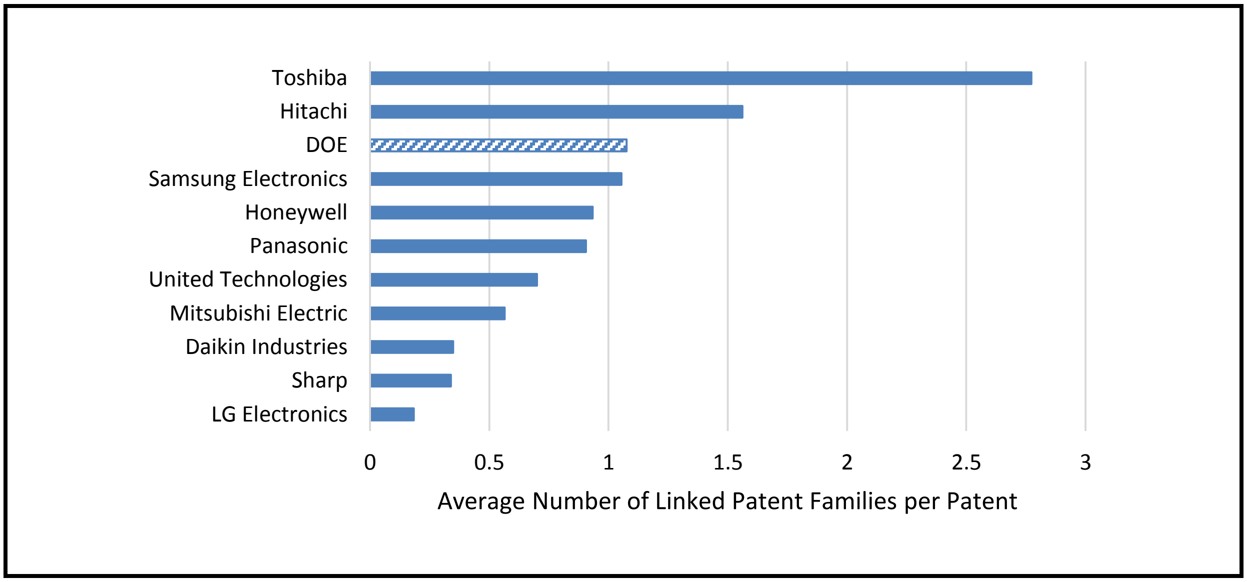


Note: For derivation of this list of companies, see Appendix B.

Figure 5-10 adjusts for the large differences in the size of patent portfolios among the organizations by using the mean number of linked patent families per patent rather than total, and also removes self-citations. This provides a measure of the average impact of individual patents in each organization's portfolio. After these adjustments, BTO, with an average of 1.07 linked families to its HVAC set, ranks third, behind only Toshiba and Hitachi. The results suggest that although BTO has a small HVAC patent portfolio, it has a relatively strong impact for its size.

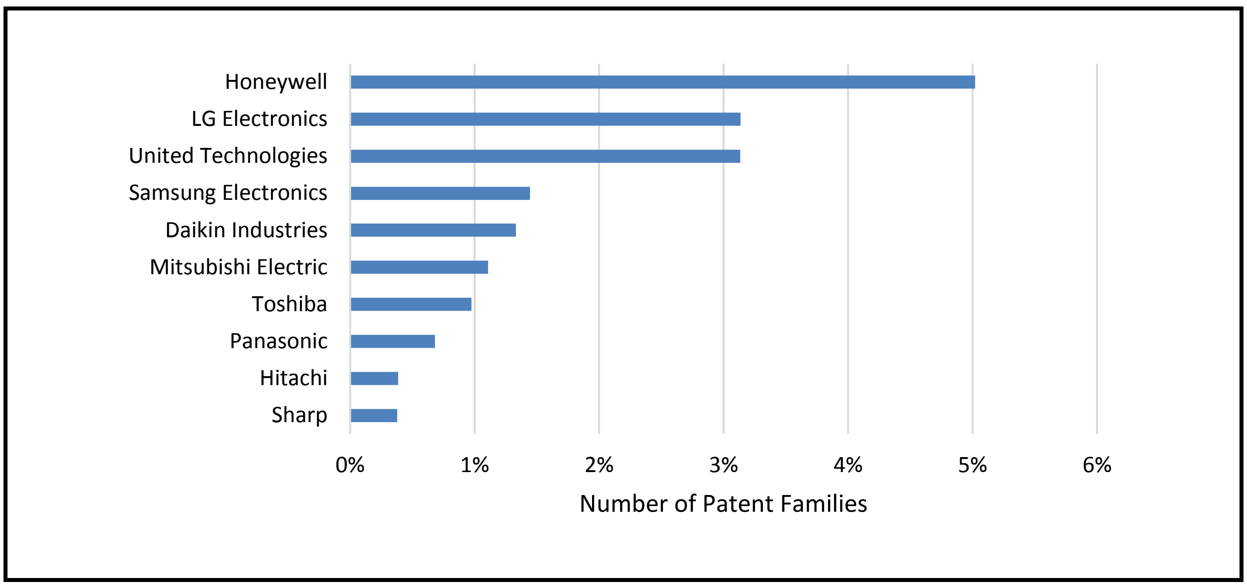
While Figure 5-10 compares the impact of BTO's HVAC patents against the impact of patents owned by leading HVAC companies, Figure 5-11 examines which of the leading companies have built most extensively on earlier BTO-HVAC patents. Figure 5-11 accounts for portfolio size bias by calculating the percentage of each leading company's HVAC patent families that are linked to earlier BTO-HVAC patents, rather than their absolute number. Honeywell is at the head of this figure, with 5% of its HVAC patent families linked to earlier BTO-HVAC patent families. LG Electronics and United Technologies come next, each with slightly more than 3% of their patent families linked to the BTO-HVAC patent set. Honeywell's relatively small HVAC portfolio, and LG's and United Technologies' much larger portfolios, are thus linked most extensively to earlier BTO-funded HVAC research.

Figure 5-10. Average Number of HVAC Patent Families of Leading Companies and DOE Linked to the HVAC Patent Portfolios owned by Leading Organizations



.

Figure 5-11. Percentage of Leading Companies' HVAC Patent Families Linked to Earlier BTO-HVAC Patent Families



.

Table 5-11 shows the BTO-HVAC patent families (designated by the DOE Anchor Patent #) found to be linked directly or indirectly to the largest number of subsequent patent families owned by the leading companies in HVAC. Most of the patents in this figure are relatively old. This is not surprising, since older patents have had more time to become connected to subsequent generations of technology. As such, most of the patent families in Table 6-1 represent older foundation technologies that are linked to subsequent developments made by leading companies in the HVAC industry.

Table 5-11. BTO-Appliances Patent Families Linked to the Most HVAC Patent Families of Leading Companies.

DOE Anchor Patent #	Application Date	Issue Date	Number of Linked Leading Company Families	Assignee	Title
4449376	2/18/1983	5/22/1984	18	Westinghouse Electric Corp	Indoor unit for electric heat pump
4217765	6/4/1979	8/19/1980	16	BP PLC	Heat exchanger-accumulator
4178772	10/25/1977	12/18/1979	10	Consolidated Natural Gas Service Co	Heat pump system
4312188	11/7/1979	1/26/1982	9	Consolidated Natural Gas Service Co	Heat pump system
6711470	11/16/2000	3/23/2004	8	Bechtel BWXT Idaho LLC	Method, system and apparatus for monitoring and adjusting the quality of indoor air
6778945	12/12/2001	8/17/2004	8	Battelle Memorial Institute	Rooftop package unit diagnostician
4055964	11/1/1976	11/1/1977	7	Consolidated Natural Gas Service Co	Heat pump system
5845502	7/22/1996	12/8/1998	7	Lockheed Martin Corp.	Heat pump having improved defrost system
5628200	1/12/1995	5/13/1997	5	Consolidated Natural Gas Service Co	Heat pump system with selective space cooling
5245833	5/19/1992	9/21/1993	4	Lockheed Martin Corp.	Liquid over-feeding air conditioning system and method
6467284	9/17/2001	10/22/2002	4	UT-Battelle LLC	Frostless heat pump having thermal expansion valves
4540501	9/12/1984	9/10/1985	4	US Dept of Energy	Gas hydrate cool storage system

.

The patent family at the head of Table 5-11 (whose DOE anchor patent[33] is US #4449376) is assigned to Westinghouse Electric. It describes an indoor heat pump for residential air conditioning units, and is linked to eighteen patent families assigned to leading HVAC patent families. These include patents families owned by LG Electronics and United Technologies describing indoor and outdoor air conditioning units, rain shields for outdoor appliances, and methods for disposing of condensation formed on evaporator coils. Also prominent is a BP patent family (anchor patent US #4217765) describing a heat exchanger. This family is linked to 16 subsequent families assigned to the leading HVAC companies, primarily LG Electronics families describing various components of air conditioning systems. Table 6-1 also includes several newer DOE BTO-HVAC patent families, notably a Bechtel family describing air quality monitoring (anchor patent US #6711470), and a Battelle patent describing an HVAC diagnostic system (anchor patent US #6778945).

High-impact HVAC patents owned by Leading companies that Link back to the BTO-HVAC patents were also identified by backward tracing. An example is US #5761921, assigned to Toshiba, describing a low-cost, smaller-sized air conditioning system. Another is US #5503222, a Honeywell patent describing a heat exchanger for air conditioning or waste heat recovery.

5.8.5 Most Influential Attributed Patents

The patents in Table 5-12 are a mix of older patents that have received large numbers of citations from subsequent generations of patents, and more recent patents that have attracted more citations than expected. One advantage of using Citation Indexes is that these two groups of patents can be compared directly, since each is benchmarked against its own peer group of patents of a similar age and technology.

The two patents at the head of Table 5-12, US #6037032 and US #6399149, both describe carbon foams designed for use as heat sinks. These patents both resulted from research performed by Oak Ridge National Lab (ORNL), and are assigned to the managers of that lab (Lockheed Martin for the first

[33] The anchor patent for each patent family is a single patent from the family, generally the first patent issued, but it is not necessarily the priority filing (which may, for example, be a Japanese application).

patent, and UT-Battelle for the second, since UT-Battelle took over management of ORNL from Lockheed in 2000). The first of these patents has been cited by 80 subsequent patents (Citation Index = 5.08), while the second has been cited by 54 subsequent patents (Citation Index = 4.27). The ORNL heat sink technology's influence on subsequent technological developments appears strong.

More recent highly cited BTO-HVAC patents in Table 5-12 include US #7322205, a patent granted in 2008 to the Gas Technology Institute, describing a rooftop cooling system. It has been cited by 16 subsequent patents, more than three times as many citations as expected given its age and technology. Another relatively recent patent in Table 5-12 is US #7269966, granted in 2007 to AIL Research, and describing a heat and mass exchanger designed to regulate both temperature and humidity in buildings. It has been cited by 17 subsequent patents, more than three times as many citations as expected. Slightly older is US #6,880,344, a 2005 patent assigned to UTC Power (now owned by ClearEdge Power), that describes an organic Rankine cycle designed for turbine cooling systems. It has been cited by 38 subsequent patents, almost four times as many citations as expected.

Another patent of interest in Table 5-12 is US #5,477,914, granted to Climate Master in 1995. It describes a ground source heat pump. This Climate Master patent has been cited by 45 subsequent patents, which is almost three times as many citations as expected for a patent of its age and technology.

Table 5-12. Highly Cited BTO-attributed HVAC Patents Overall.

DOE Patent #	Application Date	Issue Date	Number of Citations Received	Citation Index	Assignee	Title
6037032	6/8/1998	3/14/2000	80	5.08	Lockheed Martin Corp.	Pitch-based carbon foam heat sink with phase change material
6399149	1/24/2000	6/4/2002	54	4.27	UT-Battelle LLC	Pitch-based carbon foam heat sink with phase change material
6880344	6/17/2003	4/19/2005	38	3.68	ClearEdge Power Inc	Combined rankine and vapor compression cycles
5157893	6/12/1990	10/27/1992	63	3.66	Midwest Research Institute	Compact vacuum insulation
4189848	8/1/1977	2/26/1980	41	3.44	US Dept of Energy	Energy-efficient regenerative liquid desiccant drying process
6276155	12/22/2000	8/21/2001	41	3.37	UT-Battelle LLC	Personal cooling apparatus and method
4825939	7/1/1986	5/2/1989	44	3.27	University of Dayton	Polymeric compositions incorporating polyethylene glycol as a phase change material
7322205	7/7/2004	1/29/2008	16	3.21	Gas Technology Institute	Hydronic rooftop cooling systems
7269966	11/1/2005	9/18/2007	17	3.20	AIL Research Inc	Heat and mass exchanger
4732008	11/1/1986	3/22/1988	49	3.14	US Dept of Energy	Triple effect absorption chiller utilizing two refrigeration circuits
5477914	9/7/1994	12/26/1995	45	2.96	Climate Master Inc	Ground source heat pump system comprising modular subterranean heat exchange units with multiple parallel secondary conduits
6711470	11/16/2000	3/23/2004	45	2.57	Bechtel BWXT Idaho LLC	Method, system and apparatus for monitoring and adjusting the quality of indoor air
6378605	12/2/1999	4/30/2002	29	2.51	Midwest Research Institute	Heat exchanger with transpired, highly porous fins
5245833	5/19/1992	9/21/1993	34	2.20	Lockheed Martin Corp.	Liquid over-feeding air conditioning system and method

.

5.8.6 Summary of Findings

The patent analysis produced the following principal findings attributed to BTO's funding of HVAC R&D:

- A total of 162 HVAC patents attributed to BTO funding—comprised of 115 US patents, 19 EPO patents, and 28 WIPO patents--were grouped into 106 patent families.
- The number of BTO HVAC patent families counts rose and then declined sharply after 2005. Meanwhile, overall HVAC patenting continued to increase throughout the period -- consistent with BTO performing earlier, foundational work that is subsequently built on by others.
- Using citation analysis to trace forward from BTO-HVAC patents showed that they are linked extensively to subsequent patents in the patent classification associated with Refrigeration Systems. This suggests that DOE's influence has been particularly strong upon developments related to the underlying refrigeration cycle of air conditioning systems, rather than to mechanical components such as blowers, vents, housings, etc.
- Tracing forward also revealed that BTO's HVAC patents are linked to subsequent developments related to cooling systems for electronics and integrated circuits, showing a spillover influence of DOE's HVAC research into other areas than heating and cooling of buildings.
- Preparatory work for the backward tracing analysis showed that BTO's HVAC portfolio (106 patent families) is much smaller than those associated with the leading companies in the industry. The largest HVAC patent portfolios are owned by Daikin Industries (1,278 patent families) and Mitsubishi Electric (1,265), LG Electronics (957), Panasonic (883), United Technologies (798), Samsung (346), Toshiba (308), Sharp (265), Hitachi (260), and Honeywell (239).
- The backward patent citation tracing revealed that BTO's 106 HVAC patent families are linked to 114 subsequent HVAC patent families owned by the leading HVAC companies, which when adjusted for size difference and

self-citations resulted in an average of 1.07 links per BTO family. This average puts BTO third when ranked against the leading companies in terms of impact per patent family--behind Toshiba (2.77 links per family, and behind Hitachi (1.56). It puts BTO significantly ahead of Daikin (0.35), Sharp (0.34) and LG Electronics (0.18). Thus, although DOE has a relatively small HVAC patent portfolio, the patents have had a comparatively strong impact.

- The backward tracing showed that, among the leading companies, HVAC patent families owned by LG Electronics, United Technologies and Honeywell are linked particularly extensively to BTO- HVAC patents.
- The forward and backward tracing together identified high-impact individual BTO-attributed patents overall—i.e., considering citations both within and outside the targeted application area. Of the BTO-HVAC patent set, ORNL-assigned patents describing carbon forms designed for use as heat sinks have been particularly influential, as have patents describing rooftop cooling systems and heat and mass exchangers. Also of interest is a highly-cited Climate Master patent describing a ground source heat pump.

6 Heat Pump Water Heating Technology

This section describes BTO R&D related to the heat pump water heating technology and presents a knowledge benefits analysis based on water heating patenting and patent citations. No benefits were quantified for water heating technology. This section does not contribute benefits to overall estimates of investment performance metrics.

6.1 TECHNOLOGY OVERVIEW

DOE funded the development of the first unitized heat pump water heater from 1977 to 1982. Energy Utilization Systems commercialized the Tempcor model in 1982, but it was commercially unsuccessful. DOE's second effort funded A.D. Little, from 1997 to 2001, to develop a unit that was commercialized by EMI as the Watter$aver; it was also not commercially successful.[34] However, A.D. Little's involvement in this project was critical to TIAX (formerly A.D. Little) winning a contract with the California Energy Commission (CEC) for design refinement and demonstration of a market-optimized heat pump water heater.

The development of the GeoSpring by General Electric, from 2008 to 2009 under a CRADA with ORNL, built on the earlier DOE-funded work by A.D. Little/TIAX. The GeoSpring was commercialized in 2009. DOE testing for appliance EnergyGuide labeling confirmed that the GeoSpring heat pump uses 62%

[34] One interviewee suggested that part of the reason the Watter$aver struggled commercially had to do with a supply chain problem. The product relied on a specialized component that the part supplier discontinued.

less energy than a standard 50-gallon electric water heater. GeoSpring was the first ENERGY STAR-qualified heat pump water heater and also qualifies for the federal 30% residential energy efficiency tax credit and numerous state and local utility rebates/incentives.

General Electric was probably not the only company that benefited from the DOE- and CEC-funded work by A.D. Little/TIAX. A number of other companies have also recently commercialized heat pump water heaters; these include Rheem, A.O. Smith, and Sanden. It is plausible that knowledge spillovers played a part, although our analysis did not explore this possibility in any detail.

Annual sales in the United States were 43,000 in 2013 and 55,000 in 2015 according to Energy Star Unit Shipment and Market Penetration Report, Calendar Year 2013 Summary and Calendar Year 2015 Summary.

6.2 KNOWLEDGE BENEFITS

This section assesses selected knowledge benefits resulting from BTO's funding of R&D in water heating technologies, including and especially heat pump water heating technology.

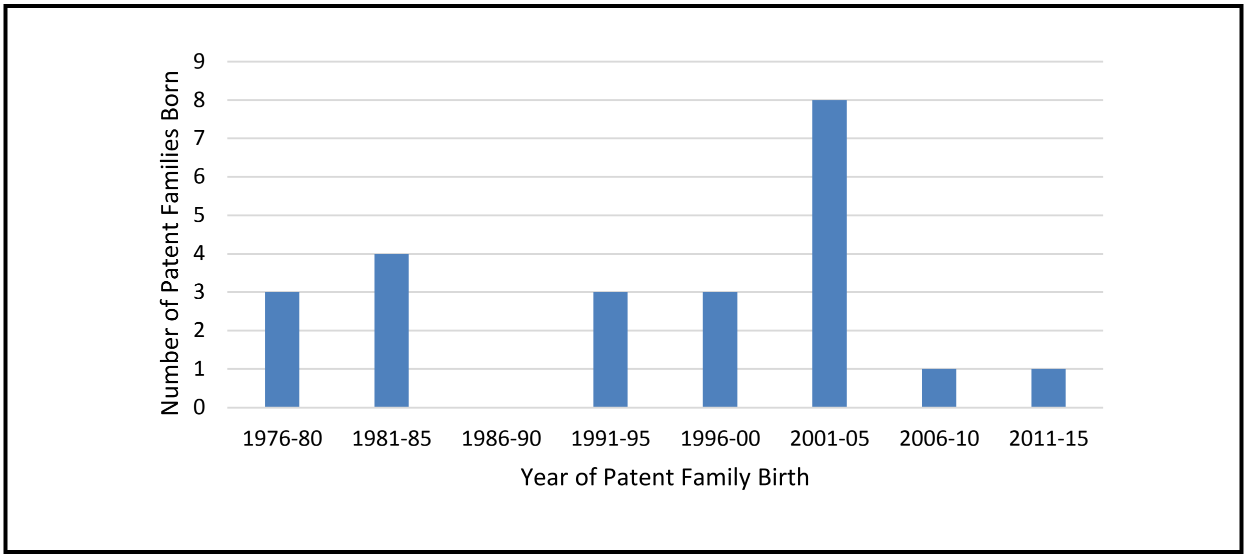
6.2.1 Trends in Attributed Patenting

Figure 6-1 shows two bursts of activity in BTO-attributed water heating patenting: 7 patent families were born from 1978 to 1983 and 8 were born from 2001 to 2005. These bursts correspond to heat-pump water heating technology research pursued at those times by BTO.

The upward trend in water heating technology patenting activity by all organizations beginning in 2000 (Figure 6-2) reflects the interest finally taken in heat-pump water heating technology by industry.[35]

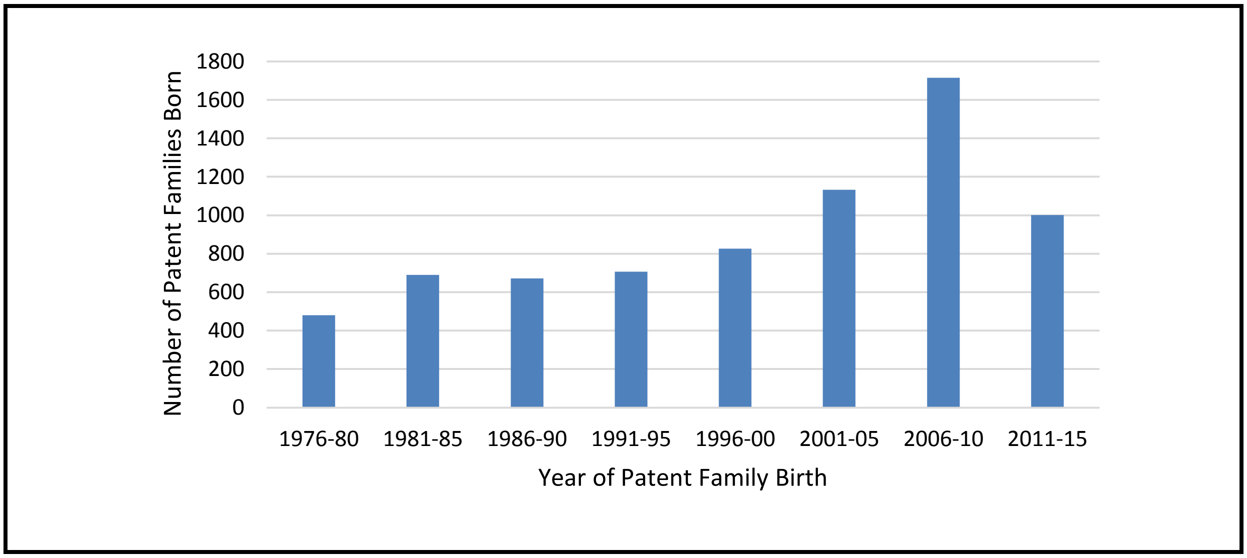
[35] The number of patent family births in 2011-2015 is biased downward by time lags in the patenting process; most patent families filed in 2015, and possibly in 2014, had not yet been issued when this analysis was carried out.

Figure 6-1. Trend in BTO-Attributed Water Heating Patent Family Births



Note: Patent families are assigned to the year of the first patent application in the family.

Figure 6-2. Trend in All Water Heating Patent Family Births



Note: Patent families are assigned to the year of the first patent application in the family.

6.2.2 Assignees of Attributed Patents

DOE is the most prolific assignee with five patent families, followed by the Gas Technology Institute with 4 families. No other assignee has more than two BTO-attributed Water Heating patent families, including Advanced Mechanical Technology (2), Thermacore Inc. (2), Battelle Memorial Institute (1), Energy Utilization Systems (1), Lockheed Martin

(1), Nordyne LLC (1), TIAX LLX (1), University of Florida (1), and UT-Battelle (1).

6.2.3 Influence of Attributed Patents: Forward Tracing

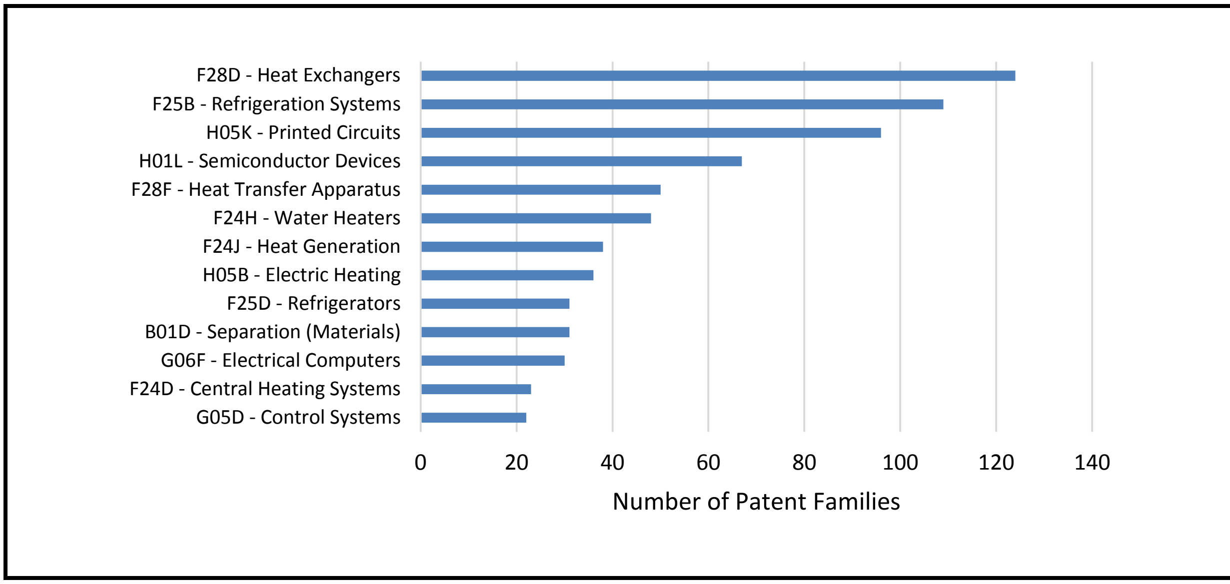
This section reports the results of starting with BTO-Water Heating patents and tracing forwards in time through two generations of citations. This analysis shows the influence of BTO-funded research on subsequent technological developments both within and outside the Water Heating industry, revealing the broader influence of BTO-funded Water Heating research.

To facilitate the analysis, the primary International Patent Classifications (IPCs) of the patent families that are linked directly and indirectly to earlier BTO-Water Heating patent families36 were identified. Figure 6-3 shows the 4-digit IPCs with the largest number of patent families that cite BTO-Water Heating patents directly as prior art and also indirectly through adding a second generation of citations. Interestingly, this figure is not headed by the IPC for Water Heaters (F24H), nor would it be if only direct citations were considered.

Heat Exchangers (IPC F28D) heads the bar chart shown in Figure 6-3. This is followed by Refrigeration Systems (IPC F25B). Adding the second level of citations increases the prominence of some other IPCs – notably Printed Circuits (H05K) and Semiconductor Devices (H01L). Most of the patents in these IPCs that are linked to earlier BTO-Water Heating patents describe heat transfer methods, especially for cooling computers and integrated circuits. The results reflect the influence of BTO-funded Water Heating research in the use of heat energy output by air conditioning systems to improve the efficiency of water heaters. The results also show how the influence of BTO's Water Heating research broadens beyond the targeted technology area yielding knowledge spillover benefits.

[36] In some cases, different patent documents within a patent family may have different first IPCs, although it is unusual for the IPCs to differ at the 4-digit level used here. To simplify the analysis, we used the primary IPC from the anchor patent in each patent family.

Figure 6-3. Patent Families Linked to BTO-Attributed Prior Water Heating Patents by IPC



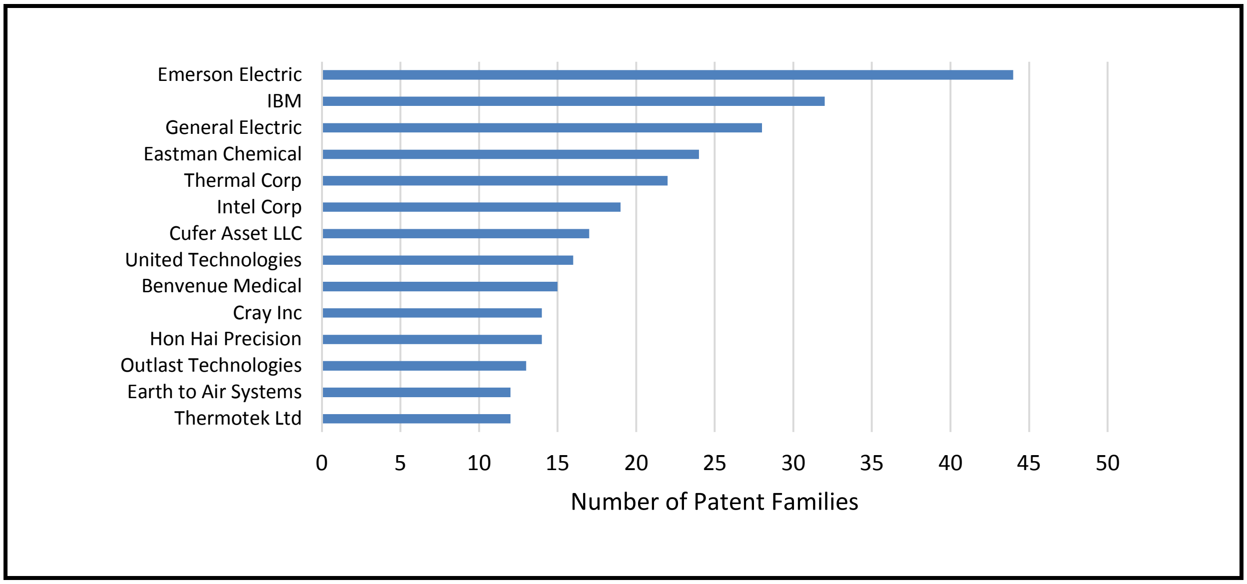
Note: IPC = International Patent Classification.

The organizations with the largest number of patent families linked directly or indirectly to earlier BTO- Water Heating patents are shown in Figure 6-4. This figure includes patent families assigned to all organizations, and includes all patent families from these organizations, not just patent families describing Water Heating technology.

Emerson Electric is at the head of Figure 6-4, with 44 patent families linked to the BTO-Water Heating patent set. Most of these Emerson families were originally assigned to Cooligy, which Emerson acquired in 2005. These families describe heat exchangers used in cooling systems for electronics and microprocessors. IBM is listed second in Figure 6-4, with 32 patent families linked to BTO-Water Heating patents. These IBM patent families also describe cooling systems for electronics. General Electric is third in this figure, with 28 linked families, covering a broader range of technologies, from heat recovery and heat sinks, to NOx removal and gas turbines.

The variety of technologies linked to BTO's Water Heating patents suggests that these patents have had a relatively broad influence extending well beyond Water Heating technology. The companies affected are also diverse.

Figure 6-4. Organizations with the Greatest Numbers of Patent Families Linked to BTO-Attributed Prior Water Heating Patents by IPC

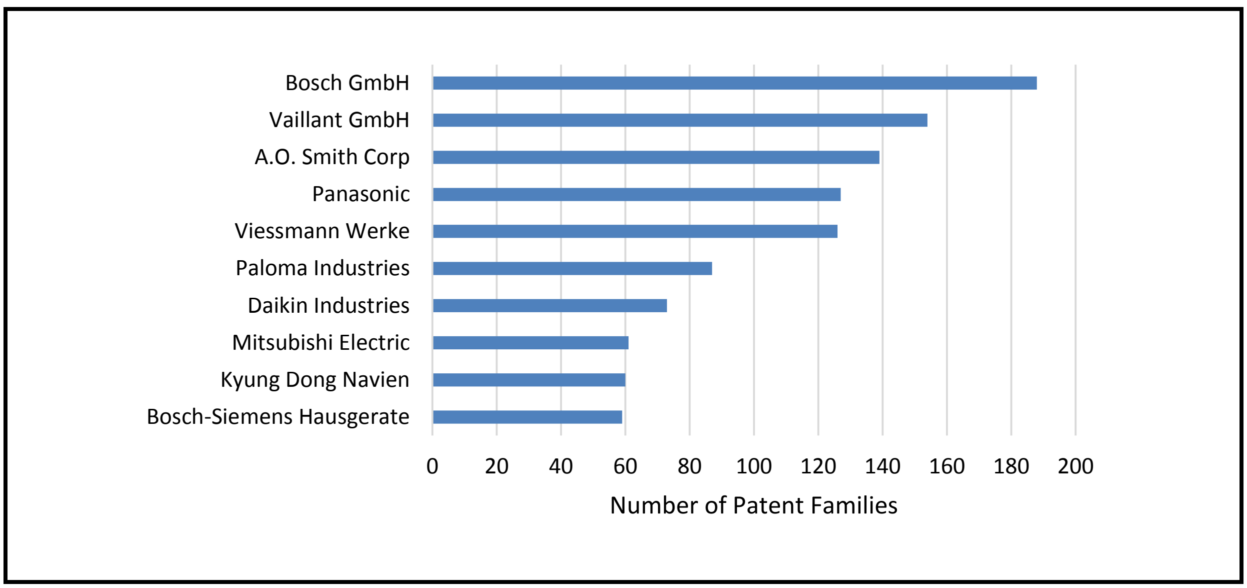


.

6.2.4 Influence of Attributed Patents: Backward Tracing

The ten companies with the largest number of Water Heating patent families (including all variant and subsidiary names) are shown in Table 6-5. The Water Heating patent families of these ten companies form the starting point of the backward tracing in this technology.

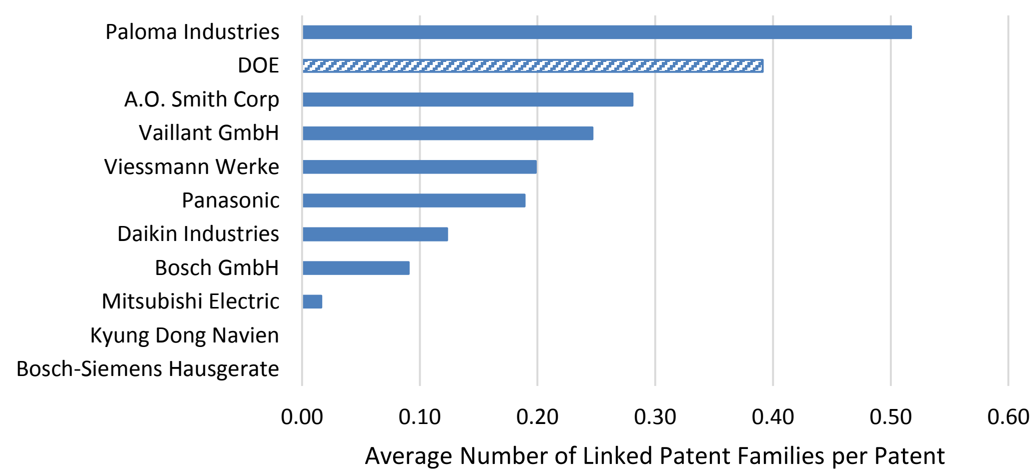
Figure 6-5. Companies with the Ten Largest Water Heating Patent Portfolios



Note: For derivation of this list of companies, see Appendix B.

Figure 6-6 shows that DOE's average of 0.39 linked families—adjusted for portfolio size bias and self-citations—ranks second, behind Paloma's. The result suggests that the overall impact of the DOE patent portfolio is limited by its small size and not by the robustness of the BTO-Water Heating patents.

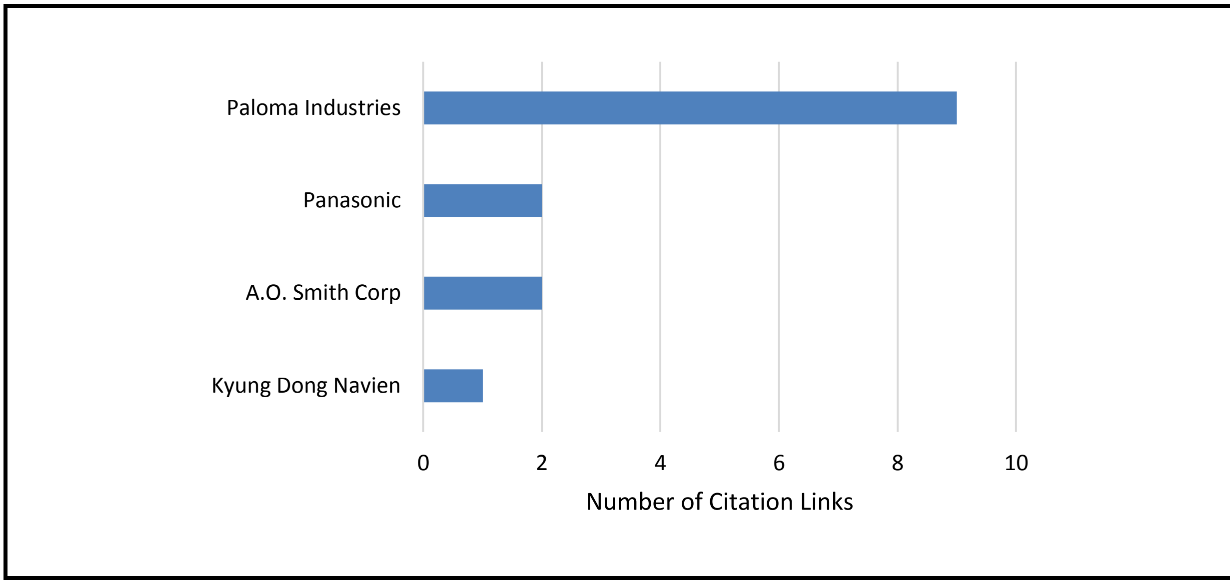
Figure 6-6. Average Number of Water Heating Patent Families of Leading Companies and DOE Linked to the Water Heating Patent Portfolios owned by Leading Organizations



.

The total number of citation links from the leading companies to the BTO-Water Heating patent set is shown in Figure 6-7. Paloma Industries (a Japanese appliance manufacturer) leads by a wide margin, with a total of nine links back to the BTO set.

Figure 6-7. Total Number of Citation Links from Leading Companies' Water Heating Patent Families to Earlier BTO-Water Heating Patent Families



Note: Companies without citation links to BTO-Water Heating families are omitted.

Table 6-1 lists the BTO-Water Heating patent families linked most strongly to the Water Heating Patent Families of the 10-top leading Water Heating companies. Almost all of the patent families in the table represent older foundation technologies that are linked to subsequent developments made by leading companies. Few patent families are listed.

The patent family at the head of Table 6-1 is related to heat pump water heaters. This patent family (with anchor patent US #5946927) is assigned to Arthur D Little Inc. and describes a low-cost hot water heater based on heat pump technology. This family is linked to four subsequent Water Heating patent families owned by leading companies. These include two patent families assigned to Rheem (a subsidiary of Paloma) describing heat pump water heaters, plus an A.O. Smith family outlining a door assembly for a water heater, and a Panasonic family describing a hot water supply system.

Another patent family near the head of Table 6-1 is an old Energy Utilization Systems family (anchor patent US #4173872, filed in 1978). This family describes a method for converting conventional hot water tanks to enable them to utilize heat output by the refrigeration circuit of air conditioning systems. It is linked to four subsequent Water Heating patent families owned by leading companies. These consist of two

Paloma (Rheem) families describing water heating that utilizes heat energy output by air conditioning systems; one Panasonic family detailing a heat pump water heater; and a Navien family outlining a hot water tank incorporating a heat exchanger.

Table 6-1. BTO Water Heating Patent Families Linked to the Most Water Heating Patent Families of Leading Companies.

DOE Anchor Patent #	Application Date	Issue Date	Number of Linked Leading Company Families	Assignee	Title
5946927	4/14/1998	9/7/1999	4	Arthur D Little Inc	Heat pump water heater and storage tank assembly
4173872	2/1/1978	11/13/1979	4	Energy Utilization Systems Inc	Water heater apparatus
4390008	06/26/1980	6/28/1983	2	US Dept of Energy	Hot water tank for use with a combination of solar energy and heat pump desuperheating
6675746	5/16/2001	1/13/2004	1	Advanced Mechanical Technology Inc	Heat exchanger with internal pin elements
5906109	7/3/1998	5/25/1999	1	Arthur D Little Inc	Heat pump water heater and storage tank assembly
6233958	9/15/1999	5/22/2001	1	Lockheed Martin Corp.	Heat pump water heater and method of making the same
4523629	9/30/1982	6/18/1985	1	US Dept of Energy	Method and apparatus for operating an improved thermocline storage unit

.

The backward tracing also revealed comparatively high-impact Water Heating patents owned by leading companies that have links back to the BTO-Water Heating set. Of most interest is the patent family designated by anchor patent US #7258080. It has been cited by 13 subsequent patents, which is 50% more citations than expected given its age and type. This patent is assigned to Paloma (Rheem) and describes a water heater with a dual tank structure.

6.2.5 Most Influential Attributed Patents

Table 6-2 lists highly cited BTO-Water Heating patents. The patents in Table 6-2 are a mix of old patents from the early 1980s, and newer patents from the late 1990s and early 2000s. As noted earlier, an advantage of using Citation Indexes is that it allows older and newer groups of patents to be compared directly, since each is benchmarked against its own peer group of patents of a similar age and technology.

Among the old patents are a 1983 DOE-assigned patent describing a hot water tank utilizing solar energy (US #4,390,008) and a Thermacore patent outlining a heat pipe that can be frozen and thawed repeatedly without being damaged (US #4,248,295). More recent patents attributed to BTO include the two listed at the head of Table 6-2. One of these patents (US #5,687,706) was granted in 1997 to the University of Florida, and describes a water heater incorporating phase change material to store heat. This patent has been cited by 37 subsequent patents, which is more than three times as many citations as expected for a patent of its age and technology. The second patent is a 2003 patent assigned to the Gas Technology Institute, which describes a NOx-reducing burner for boilers. It has been cited by 19 subsequent patents, almost three times as many citations as expected.

Table 6-2. Highly Cited BTO-attributed Water Heating Patents Overall.

DOE Patent #	Application Date	Issue Date	Number of Citations Received	Citation Index	Assignee	Title
5687706	4/25/1995	11/18/1997	37	3.04	University of Florida	Phase change material storage heater
6663380	9/5/2001	12/16/2003	19	2.80	Gas Technology Institute	Method and apparatus for advanced staged combustion utilizing forced internal recirculation
4390008	26-06-80	6/28/1983	19	2.23	US Dept of Energy	Hot water tank for use with a combination of solar energy and heat pump desuperheating
4248295	17-01-80	2/3/1981	22	2.04	Thermacore Inc	Freezable heat pipe
5946927	4/14/1998	9/7/1999	17	1.46	Arthur D Little Inc	Heat pump water heater and storage tank assembly
6233958	9/15/1999	5/22/2001	14	1.36	Lockheed Martin Corp.	Heat pump water heater and method of making the same
6814070	1/6/2003	11/9/2004	8	1.28	Gas Technology Institute	Molded polymer solar water heater
4336837	11-02-81	6/29/1982	12	1.14	US Dept of Energy	Entirely passive heat pipe apparatus capable of operating against gravity

.

6.2.6 Summary of Findings

The patent analysis produced the following principal findings attributed to BTO’s funding of Water Heating R&D:

- A total of 33 Water Heating patents attributed to BTO funding of R&D--comprised of 25 US patents, 2 EPO patents, and 6 WIPO patents--were grouped into 23 patent families

- In terms of trends, the number of BTO-attributed Water Heating patent families remained relatively low throughout the period examined (1976-2015). Between 1976 and 2000, there were a total of 13 such families. Then there was an increase in activity, with eight patent families having a priority year between 2001 and 2005. Since then, there have been only two further BTO-Water Heating patent families attributed to BTO funding. At the same time, overall patenting in Water Heating by all parties increased throughout the period examined.

- The forward tracing showed the BTO’s Water Heating patents to be linked to patents related to Refrigeration Systems and Heat Exchangers, as well as to subsequent developments in heat pump water heaters and the use of residual heat from air conditioning systems in water heaters. This reflects the influence of BTO-funded research on the use of heat energy output by air conditioning systems to improve the efficiency of water heaters.

- Preparation for tracing backward from the leading innovators in Water Heating technology to BTO’s Water Heating patent portfolio showed that the BTO’s patent portfolio in Water Heating is also much smaller than the Water Heating patent portfolios held by the leading companies in the Water Heating industry, though the difference is less extreme. BTO’s 23 patent families are compared against those of Bosch (188 families), Vaillant (154), A.O. Smith (139), Panasonic (127), Viessmann (126), Paloma (87 families), Daikin (73), Mitsubishi Electric (61), Kyung Dong Navien (60), and BSH Hausgeräte (59).

- The backward tracing revealed that BTO’s 23 Water Heating patent families are linked to only nine Water

Heating patent families owned by the leading companies— not surprising given the small size of the BTO-Water Heating patent portfolio. At the same time, BTO's average of 0.39 links per patent family ranks second--behind only that of Paloma--when compared with the average links of patents of the leading companies.

- Among the particularly influential BTO-Water Heating patents overall—that is, both within and outside the targeted technology area--is one owned by Arthur D. Little describing a low-cost hot water heater based on heat pump technology. Other influential patents were a patent describing a water heater incorporating phase change materials to store heat, assigned to the University of Florida, and a patent describing a NOx-reducing burner for boilers assigned to the Gas Technology Institute.

7 Retrospective Economic Impact Assessment

This section collects the quantified benefits for the three selected technology areas and compares them with BTO R&D investment costs to develop the main retrospective investment performance metrics.

7.1 BUILDING TECHNOLOGIES OFFICE RESEARCH INVESTMENTS

Table 7-1 summarizes BTO investments in HVAC, water heating, and appliance R&D from 1976 through 2015.[37] These investments comprise one of four long-standing R&D portfolios within BTO's Emerging Technologies Program. The other three portfolios in the Emerging Technologies Program address the technology areas of 1) lighting, 2) windows and building envelope, and 3) building energy modeling.[38] Investments are discounted back to the beginning of 1976 at 7% and 3%, assuming that each year's investment cost was incurred at the beginning of the year. Thus, 1976 costs are undiscounted, 1977 costs are discounted by one year, etc.

Recall, the three technology areas for which benefits were quantified for this study are only a small subset of BTO's HVAC, water heating, and appliance R&D portfolio, which has also included, e.g., thermally activated heat pumps, combustion and thermal distribution, and household appliances like dishwashers and clothes washers and dryers. Additional examples are described in Section 6 and Section 2.6.1.

[37] DOE was established on October 1, 1977. The analysis includes investments in building technologies made by DOE's predecessor agencies in 1976 and the beginning of 1977.

[38] More recently, BTO has added R&D portfolios addressing sensors and controls and transactive energy.

Table 7-1. BTO HVAC, Water Heating, and Appliance R&D Portfolio Investment Costs

Year	Nominal (thousands)	Constant 2015 dollars (thousands)	Constant 2015 dollars (thousands) Discounted at 7%	Constant 2015 dollars (thousands) Discounted at 3%
1976	2,693	11,210	11,210	11,210
1977	3,405	13,313	12,442	12,925
1978	8,200	29,787	26,017	28,077
1979	19,250	62,854	51,308	57,521
1980	26,600	76,521	58,378	67,988
1981	11,300	29,451	20,998	25,404
1982	8,520	20,917	13,938	17,518
1983	8,700	20,705	12,894	16,835
1984	8,050	18,356	10,683	14,491
1985	8,993	19,808	10,774	15,181
1986	7,621	16,466	8,370	12,252
1987	7,450	15,540	7,383	11,226
1988	8,498	17,028	7,561	11,943
1989	9,743	18,630	7,731	12,686
1990	10,412	18,886	7,324	12,486
1991	11,613	20,212	7,326	12,973
1992	10,274	17,354	5,878	10,814
1993	10,893	17,869	5,657	10,811
1994	12,306	19,676	5,821	11,558
1995	13,107	20,385	5,637	11,625
1996	10,011	15,126	3,909	8,375
1997	11,440	16,890	4,079	9,079
1998	12,390	18,014	4,066	9,401
1999	14,833	21,103	4,452	10,693
2000	5,940	8,175	1,612	4,022
2001	6,735	9,016	1,661	4,306
2002	7,484	9,860	1,698	4,572
2003	6,146	7,917	1,274	3,564
2004	7,303	9,162	1,378	4,004
2005	7,021	8,521	1,198	3,616
2006	10,839[a]	12,744	1,674	5,250
2007	2,919	3,336	410	1,335
2008	2,845	3,132	359	1,216
2009	7,040	7,776	834	2,932
2010	15,500	16,845	1,688	6,166
2011	15,093	15,903	1,490	5,652
2012	16,000	16,516	1,446	5,698
2013	22,776	23,170	1,896	7,762
2014	16,968	16,988	1,299	5,525
2015	18,277	18,277	1,306	5,771
Total		743,439	335,057	494,463

Notes: Nominal costs converted to constant 2015 dollars using Consumer Price Index for All Urban Consumers: All Items, Annual, Seasonally Adjusted. [a]Nominal investment cost for HVAC, water heating, and appliances could not be separated from other Emerging Technologies R&D in 2006 and was estimated to be 33% of the total Emerging Technologies R&D portfolio cost in that year. This is considered an upper bound estimate because HVAC, water heating, and appliance R&D was at least 30% of the Emerging Technologies portfolio only in 2013, 2014, and 2015; it was less than 25% in 2004 and 2005 and less than 10% in 2007 and 2008.

7.2 ATTRIBUTABLE ECONOMIC BENEFITS

Table 7-2 summarizes energy and resource benefits over the three technologies. Benefits are discounted back to the beginning of 1976 at 7% and 3%, assuming that each year's investment cost was incurred at the end of the year.

Table 7-2. Total Retrospective Energy and Resource Benefits, Summed over the Three Technologies

	Undiscounted (millions of 2015 dollars)			Discounted at 7% (millions of 2015 dollars)			Discounted at 3% (millions of 2015 dollars)		
Year	Low	Mid	High	Low	Mid	High	Low	Mid	High
1978	1	1	1	0	1	1	1	1	1
1979	3	4	5	2	3	4	2	4	5
1980	11	14	18	8	10	13	9	12	15
1981	39	54	69	26	36	46	33	45	58
1982	108	141	173	67	88	108	88	114	141
1983	173	231	289	101	134	168	137	182	228
1984	244	336	428	133	183	233	187	258	328
1985	293	428	563	149	218	286	218	319	419
1986	223	359	495	106	170	235	161	259	358
1987	305	510	714	135	226	317	214	358	501
1988	307	541	775	127	224	322	209	368	528
1989	392	703	1,014	152	273	393	259	465	671
1990	439	799	1,160	159	290	421	282	513	745
1991	426	807	1,189	144	274	403	266	503	741
1992	496	977	1,460	157	309	462	300	591	883
1993	586	1,190	1,798	173	352	532	344	699	1,056
1994	682	1,420	2,166	189	393	599	389	810	1,235
1995	761	1,620	2,490	197	419	643	422	897	1,378
1996	888	1,897	2,922	215	458	706	478	1,020	1,571
1997	965	2,092	3,237	218	472	731	504	1,092	1,689
1998	998	2,211	3,448	211	466	727	506	1,120	1,747
1999	1,093	2,438	3,812	215	481	751	537	1,199	1,875
2000	1,268	2,808	4,381	234	517	807	606	1,341	2,093
2001	1,314	3,007	4,740	226	518	816	609	1,394	2,198
2002	1,332	3,123	4,960	214	503	798	600	1,406	2,233
2003	1,432	3,457	5,534	215	520	832	626	1,511	2,419
2004	1,534	3,759	6,046	216	528	850	651	1,595	2,566
2005	1,736	4,202	6,743	228	552	886	715	1,731	2,778
2006	2,042	4,880	7,822	251	599	960	817	1,952	3,129
2007	2,184	5,198	8,342	251	596	957	848	2,019	3,239
2008	2,343	5,598	9,009	251	600	966	883	2,110	3,396
2009	2,491	5,972	9,635	250	598	966	912	2,186	3,527
2010	2,557	6,149	9,945	240	576	931	909	2,185	3,534
2011	2,613	6,302	10,215	229	552	894	902	2,174	3,525
2012	2,687	6,497	10,556	220	532	864	900	2,177	3,536
2013	2,799	6,786	11,049	214	519	845	910	2,207	3,594
2014	2,955	7,189	11,736	211	514	839	933	2,270	3,706
2015	3,099	7,565	12,380	207	505	827	950	2,319	3,795
Total	43,819	101,266	161,321	6,540	14,209	22,139	18,315	41,407	65,440

Notes: These totals include only the dollar-denominated energy and resource benefits. Environmental health benefits are not included.

Table 7-3 summarizes total monetized benefits—energy and resource benefits plus environmental health benefits—over the three technologies. Environmental health benefits are based on the lower numbers of adult mortality and non-fatal heart attacks estimated by COBRA. Benefits are discounted back to the beginning of 1976 at 7% and 3%, assuming that each year's investment cost was incurred at the end of the year.

Table 7-3. Total Monetized Benefits, Summed over the Three Technologies

	Undiscounted (millions of 2015 dollars)			Discounted at 7% (millions of 2015 dollars)			Discounted at 3% (millions of 2015 dollars)		
Year	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
1978	1	1	2	1	1	1	1	1	2
1979	4	6	8	3	4	5	3	5	7
1980	13	18	23	9	12	16	11	15	19
1981	52	76	100	33	48	63	43	62	82
1982	143	195	246	85	115	145	114	155	196
1983	236	327	418	131	181	230	182	252	322
1984	337	481	626	175	248	322	253	361	468
1985	421	637	853	203	305	408	306	462	619
1986	389	640	891	171	281	390	272	447	622
1987	513	878	1,243	212	361	511	349	596	844
1988	556	994	1,432	213	380	547	366	654	942
1989	672	1,224	1,776	242	440	637	430	784	1,137
1990	738	1,370	2,003	248	461	673	459	852	1,245
1991	768	1,474	2,180	240	460	680	463	887	1,312
1992	927	1,842	2,761	270	535	802	541	1,075	1,612
1993	1,108	2,265	3,431	301	615	931	628	1,283	1,944
1994	1,303	2,727	4,167	330	691	1,056	717	1,500	2,291
1995	1,379	2,930	4,502	328	698	1,073	738	1,568	2,409
1996	1,625	3,484	5,370	362	775	1,194	844	1,809	2,789
1997	1,809	3,932	6,090	375	815	1,262	911	1,980	3,067
1998	1,917	4,247	6,622	371	821	1,280	937	2,075	3,235
1999	2,140	4,777	7,469	386	861	1,347	1,014	2,264	3,540
2000	2,323	5,173	8,086	394	877	1,371	1,072	2,386	3,730
2001	2,418	5,538	8,733	383	878	1,384	1,083	2,480	3,911
2002	2,424	5,686	9,029	359	843	1,339	1,055	2,473	3,928
2003	2,579	6,213	9,942	358	862	1,380	1,090	2,626	4,202
2004	2,737	6,676	10,727	355	867	1,393	1,123	2,741	4,404
2005	3,066	7,390	11,846	372	898	1,439	1,222	2,946	4,723
2006	3,392	8,100	12,982	388	926	1,483	1,316	3,144	5,038
2007	3,483	8,290	13,303	374	889	1,427	1,315	3,130	5,022
2008	3,585	8,567	13,787	361	863	1,389	1,317	3,146	5,063
2009	3,673	8,805	14,205	347	833	1,344	1,312	3,145	5,075
2010	3,563	8,568	13,858	317	763	1,234	1,240	2,981	4,821
2011	3,480	8,392	13,604	291	703	1,139	1,179	2,842	4,606
2012	3,594	8,691	14,119	281	680	1,104	1,181	2,856	4,641
2013	3,730	9,046	14,729	273	661	1,077	1,191	2,887	4,701
2014	3,670	8,930	14,579	253	616	1,006	1,142	2,779	4,536
2015	3,661	8,936	14,623	238	581	950	1,109	2,708	4,431
Total	68,430	157,524	250,364	10,033	21,847	34,033	28,528	64,358	101,534

Notes: These totals include all dollar-denominated benefits: energy and resource benefits plus environmental health benefits. Note that, because environmental health benefits in a given year include internal discounting (reflecting expected numbers of years between pollution emissions and certain adverse health events), discounted values cannot be calculated directly from undiscounted values in this table.

7.3 RETURN ON INVESTMENT ANALYSIS

Table 7-4 summarizes net present values (NPV), benefit-to-cost ratios (BCR), and internal rates of return (IRR) taking into account only energy and resource benefits (based on the benefits summarized in Table 7-2).

Based on energy and resource benefits alone, BTO's investments are estimated to have had a NPV of between $6 billion and $22 billion and a benefit-to-cost ratio of between 20-to-1 and 66-to-1 (using a 7% discount rate), and an internal rate of return of between 38% and 51%.

Table 7-4. Retrospective Investment Performance Metrics: Energy and Resource Benefits

Metric	Low	Mid	High
NPV (millions of 2015 dollars)			
7% Discount Rate	6,205	13,874	21,804
3% Discount Rate	17,820	40,912	64,945
Benefit-to-Cost Ratio			
7% Discount Rate	20:1	42:1	66:1
3% Discount Rate	37:1	84:1	132:1
Internal Rate of Return	38%	46%	51%

Note: Benefits are retrospective: only energy savings realized through 2015 are included.

Table 7-5 summarizes net present values (NPV), benefit-to-cost ratios (BCR), and internal rates of return (IRR) taking into account total monetized benefits: energy and resource benefits plus environmental health benefits (based on the benefits summarized in Table 7-3).

With environmental health benefits included, BTO's investments have a NPV of between $10 billion and $34 billion and a benefit-to-cost ratio of between 30-to-1 and 102-to-1 (using a 7% discount rate), and an internal rate of return of between 46% and 61%.

Table 7-5. Retrospective Investment Performance Metrics: Energy and Resource Benefits and Environmental Health Benefits

Metric	Low	Mid	High
NPV (millions of 2015 dollars)			
7% Discount Rate	9,698	21,512	33,698
3% Discount Rate	28,034	63,863	101,039
Benefit-to-Cost Ratio			
7% Discount Rate	30:1	65:1	102:1
3% Discount Rate	58:1	130:1	205:1
Internal Rate of Return	46%	55%	61%

Note: Benefits are retrospective: only energy savings realized through 2015 are included.

8 Effective Useful Life Economic Impact Assessment

This section extends the retrospective analysis by also considering the remaining effective useful life of equipment installed and operating as of 2015.

8.1 ATTRIBUTABLE ECONOMIC BENEFITS

Flame-retention-head oil burner does not appear in this section because all DOE-attributed benefits for this technology are retrospective. Actual and counterfactual market shares of new burner sales had converged to 100% by 1996, meaning (under the assumption of a 15-year effective useful life) that the actual and counterfactual percentages of operating burners had converged to 100% by 2010, ending the stream of DOE-attributed benefits.

8.1.1 Residential Refrigeration

This section extends the analysis of Section 4 to consider the remaining effective useful life of refrigerators purchased through 2015. No refrigerators purchased after 2015 are considered—only the remaining useful life of refrigerators purchased in 2015 and earlier. As in section 4, we assume that the effective useful life of a refrigerator is 15 years.

The basis for this extended analysis is therefore the first-year energy savings developed in Step 1 in Section 4, summarized in Table 4-2 and reprised here as Table 8-1.

Table 8-1. Actual and Counterfactual Average Energy Consumption and First-Year Savings

Year	Actual Avg. Usage (kWh)	Low Impact Avg. Usage (kWh)	Mid Impact Avg. Usage (kWh)	High Impact Avg. Usage (kWh)	Refrig. Shipped (thous)	Low First-Year Energy Savings (GWh)	Mid First-Year Energy Savings (GWh)	High First-Year Energy Savings (GWh)
1980	1,437	1,437	1,437	1,437	5,124	0	0	0
1981	1,338	1,346	1,354	1,363	4,944	37	79	121
1982	1,340	1,347	1,355	1,364	4,364	32	69	105
1983	1,305	1,315	1,327	1,338	5,477	55	117	179
1984	1,282	1,294	1,307	1,320	5,994	71	150	230
1985	1,192	1,210	1,231	1,252	6,081	114	242	370
1986	1,210	1,227	1,247	1,266	6,510	113	240	366
1987	1,097	1,123	1,152	1,181	6,972	180	383	586
1988	1,086	1,113	1,143	1,173	7,227	193	410	628
1989	1,053	1,082	1,115	1,148	7,099	208	442	675
1990	1,033	1,064	1,098	1,133	7,101	219	465	711
1991	966	1,002	1,043	1,083	7,273	261	554	847
1992	926	965	1,009	1,052	7,761	302	642	982
1993	745	797	857	916	8,109	428	909	1,390
1994	737	790	850	910	8,652	461	981	1,500
1995	732	786	846	907	8,671	465	989	1,513
1996	746	799	858	917	9,045	476	1,012	1,547
1997	755	807	866	924	9,015	468	995	1,522
1998	768	819	876	933	9,741	497	1,055	1,614
1999	779	829	886	942	10,045	503	1,070	1,636
2000	795	844	899	954	10,169	497	1,057	1,616
2001	638	699	768	836	10,262	624	1,327	2,030
2002	587	652	725	798	10,754	696	1,479	2,262
2003	580	646	719	793	11,014	719	1,527	2,336
2004	565	631	706	781	11,953	794	1,688	2,581
2005	554	621	697	772	12,180	820	1,742	2,664
2006	574	640	714	788	12,173	800	1,701	2,601
2007	565	632	706	781	11,523	765	1,626	2,487
2008	549	617	693	769	10,312	697	1,482	2,267
2009	523	593	671	749	9,196	640	1,361	2,081
2010	517	587	666	745	10,235	717	1,524	2,330
2011	514	584	663	742	10,235	720	1,529	2,339
2012	516	586	665	744	9,493	666	1,415	2,164
2013	505	576	656	736	10,081	716	1,521	2,326
2014	500	571	652	732	10,081	720	1,529	2,339
2015	498	570	650	730	10,081	721	1,532	2,344

Notes: Reprised from Table 4-2. First-year energy savings is obtained by multiplying the number of refrigerators shipped by the difference between the actual (shipments-weighted) average usage by the counterfactual average usage. Refrigerator shipments obtained from Association of Home Appliance Manufacturers (2013).

Cumulative energy savings in each year are calculated just as they were in Section 4, by summing first-year energy savings over 15-year intervals, the only difference now being that the summations are continued beyond 2015. The final year is 2029, when refrigerators purchased in 2015, for which 2015 was considered to be the first year of operation, are in their 15th and final year of operation.

Cumulative energy savings are converted into energy cost savings by multiplying by the real price of electricity in each year. The real price of energy for 2017 to 2029 is assumed to stay constant at its 2016 level.

Our estimates attribute savings to DOE of between 246 billion and 799 billion kWh and between $30 billion and $98 billion undiscounted dollars (Table 8-2).

Table 8-2. Cumulative Energy and Energy Cost Savings: Effective Useful Life

Year	Low Energy Savings (GWh)	Mid Energy Savings (GWh)	High Energy Savings (GWh)	Real Price (2015 dollars /GWh)	Low Cost Savings (Millions of 2015 dollars)	Mid Cost Savings (Millions of 2015 dollars)	High Savings (Millions of 2015 dollars)
Total 1980-2015	170,529	362,396	554,263		20,950	44,521	68,092
2016	10,190	21,656	33,121	121,400	1,237	2,629	4,021
2017	9,494	20,177	30,859	121,400	1,153	2,449	3,746
2018	8,776	18,649	28,523	121,400	1,065	2,264	3,463
2019	7,982	16,962	25,942	121,400	969	2,059	3,149
2020	7,162	15,220	23,278	121,400	869	1,848	2,826
2021	6,362	13,519	20,677	121,400	772	1,641	2,510
2022	5,596	11,893	18,189	121,400	679	1,444	2,208
2023	4,899	10,411	15,923	121,400	595	1,264	1,933
2024	4,259	9,050	13,842	121,400	517	1,099	1,680
2025	3,542	7,527	11,512	121,400	430	914	1,398
2026	2,822	5,997	9,173	121,400	343	728	1,114
2027	2,156	4,582	7,009	121,400	262	556	851
2028	1,441	3,061	4,682	121,400	175	372	568
2029	721	1,532	2,344	121,400	88	186	285
Total 2016-2029	75,401	160,237	245,072		9,154	19,453	29,752
Total 1980-2029	245,930	522,632	799,335		30,103	63,973	97,843

Notes: Nominal energy prices are from "Average Retail Price of Electricity, Residential" (dollars per kWh, including taxes) from the U.S. Energy Information Administration. Nominal prices are converted to constant 2015 dollars using the Consumer Price Index for All Urban Consumers: All Items, Annual, Seasonally Adjusted. Prices for 2017 to 2029 are assumed to be constant at the 2016 level.

Based on the full EUL energy savings, we extend the environmental health benefits analysis using the approach described in Section 4.6. Table 8-3 reports the estimated value of avoided adverse health events at between $14 billion and $105 billion, without discounting.

Table 8-3. Value of All DOE-Attributed Avoided Adverse Health Events

	Value based on low numbers of adult mortality and non-fatal heart attacks (millions of 2015 dollars)			Value based on high numbers of adult mortality and non-fatal heart attacks (millions of 2015 dollars)		
Year	Low	Middle	High	Low	Middle	High
Total 1980-2015	12,480	26,521	40,562	28,239	60,011	91,784
2016	236	501	766	533	1,133	1,732
2017	221	470	718	500	1,062	1,625
2018	204	434	664	462	982	1,502
2019	186	395	604	420	893	1,366
2020	167	354	542	377	801	1,226
2021	148	315	481	335	712	1,089
2022	130	277	423	295	626	958
2023	114	242	371	258	548	838
2024	99	211	322	224	477	729
2025	82	175	268	187	396	606
2026	66	140	213	149	316	483
2027	50	107	163	114	241	369
2028	34	71	109	76	161	247
2029	17	36	55	38	81	123
Total 2016-2029	1,753	3,726	5,698	3,967	8,430	12,894
Total 1980-2029	14,233	30,247	46,260	32,206	68,442	104,678

Notes: Attributed avoided mortalities based amounts of pollutants abated and COBRA model parameters. Within each block of three columns, Low/Middle/High refers to the scenarios in Table 8-2. Lower values in the left block of Low/Middle/High scenarios are based on low numbers of adult mortality and non-fatal heart attacks in Table 4-7; higher values in the right block are based on high numbers for adult mortality and non-fatal heart attacks. Based on U.S. population in 2017. Totals are not discounted.

8.1.2 Heat Pumps and Central Air Conditioners

This section extends the analysis of Section 5 to consider the remaining effective useful life of heat pumps and central air conditioners purchased through 2015. No products purchased after 2015 are considered—only the remaining useful life of heat pumps and central air conditioners purchased in 2015 and earlier. As in section 5, we assume that the effective useful life of a heat pumps or central air conditioner is 15 years.

The basis for this extended analysis is therefore the first-year energy savings developed in Step 1 in Section 5, summarized in Table 5-2 and reprised here as Table 8-4.

Table 8-4. Actual and Counterfactual Shipments-Weighted Average SEER, and Numbers of Heat Pumps and Central Air Conditioners Shipped

	Shipments-Weighted Average SEER, Actual and Counterfactual				Shipments (thousands)	
Year	**Actual**	**Low DOE Impact**	**Mid DOE Impact**	**High DOE Impact**	**Heat Pumps**	**CACs**
1990	9.3	9.3	9.3	9.3	809	2,920
1991	9.5	9.5	9.5	9.5	764	3,006
1992	10.5	10.4	10.2	10.0	799	2,914
1993	10.6	10.5	10.3	10.0	882	3,188
1994	10.7	10.5	10.3	10.1	1,008	3,888
1995	10.7	10.6	10.3	10.1	1,025	4,063
1996	10.7	10.6	10.3	10.1	1,148	4,523
1997	10.7	10.6	10.3	10.1	1,131	4,229
1998	11.0	10.8	10.5	10.2	1,260	4,980
1999	11.0	10.8	10.6	10.3	1,293	5,354
2000	11.0	10.8	10.5	10.3	1,339	5,346
2001	11.1	10.9	10.6	10.3	1,442	4,835
2002	11.1	10.9	10.6	10.3	1,484	5,263
2003	11.3	11.0	10.7	10.4	1,626	5,181
2004	11.4	11.2	10.8	10.5	1,886	5,515
2005	11.4	11.2	10.8	10.5	2,137	6,471
2006	13.2	12.7	12.1	11.4	2,118	4,951
2007	13.8	13.3	12.5	11.8	1,903	4,456
2008	13.8	13.3	12.6	11.8	1,865	3,968
2009	14.0	13.5	12.7	11.9	1,642	3,516
2010	14.5	13.9	13.0	12.1	1,748	3,420
2011	14.3	13.7	12.9	12.0	1,765	3,745
2012	14.3	13.7	12.9	12.0	1,698	3,916
2013	14.4	13.8	12.9	12.1	1,969	4,201
2014	14.6	14.0	13.1	12.2	2,354	4,500
2015	14.7	14.1	13.2	12.3	2,269	4,546

Notes: Reprised from Table 5-2. CACs = central air conditioners. Shipments data from AHRI (2017).

Cumulative energy savings in each year are calculated just as they were in Section 5, by summing first-year energy savings over 15-year intervals, the only difference now being that the summations are continued beyond 2015. The final year is 2029, when heat pumps and central air conditioners purchased in 2015, for which 2015 was considered to be the first year of operation, are in their 15th and final year of operation.

Cumulative energy savings are converted into energy cost savings by multiplying by the real price of electricity in each year. The real price of energy for 2017 to 2029 is assumed to stay constant at its 2016 level.

Our estimates attribute savings to DOE of between 260 billion and 1.2 trillion kWh and between $32 billion and $143 billion undiscounted dollars (Table 8-5).

Table 8-5. Cumulative Energy and Energy Cost Savings: Effective Useful Life

Year	Low Energy Savings (GWh)	Mid Energy Savings (GWh)	High Energy Savings (GWh)	Real Price (2015 dollars /GWh)	Low Cost Savings (Millions of 2015 dollars)	Mid Cost Savings (Millions of 2015 dollars)	High Savings (Millions of 2015 dollars)
Total 1990-2015	153,671	407,046	681,628		18,748	49,675	83,209
2016	13,086	35,251	60,123	121,400	1,589	4,280	7,299
2017	12,489	33,687	57,533	121,400	1,516	4,090	6,985
2018	11,842	31,986	54,713	121,400	1,438	3,883	6,642
2019	11,092	30,014	51,437	121,400	1,347	3,644	6,244
2020	10,218	27,713	47,613	121,400	1,240	3,364	5,780
2021	9,148	24,838	42,726	121,400	1,111	3,015	5,187
2022	8,126	22,078	38,003	121,400	987	2,680	4,614
2023	7,161	19,467	33,533	121,400	869	2,363	4,071
2024	6,297	17,127	29,518	121,400	764	2,079	3,583
2025	5,384	14,644	25,238	121,400	654	1,778	3,064
2026	4,442	12,086	20,839	121,400	539	1,467	2,530
2027	3,501	9,532	16,446	121,400	425	1,157	1,996
2028	2,441	6,650	11,483	121,400	296	807	1,394
2029	1,216	3,316	5,730	121,400	148	403	696
Total 2016-2029	106,444	288,387	494,935		12,922	35,010	60,085
Total 1990-2029	260,115	695,432	1,176,564		31,671	84,685	143,295

Notes: Nominal energy prices are from “Average Retail Price of Electricity, Residential” (dollars per kWh, including taxes) from the U.S. Energy Information Administration. Nominal prices are converted to constant 2015 dollars using the Consumer Price Index for All Urban Consumers: All Items, Annual, Seasonally Adjusted. Prices for 2017 to 2029 are assumed to be constant at the 2016 level.

Based on the full EUL energy savings, we extend the environmental health benefits analysis using the approach described in Section 5.6. Table 8-6 reports the estimated value of avoided adverse health events at between $18 billion and $184 billion, without discounting.

Table 8-6. Value of All DOE-Attributed Avoided Adverse Health Events

	Value based on low numbers of adult mortality and non-fatal heart attacks (millions of 2015 dollars)			Value based on high numbers of adult mortality and non-fatal heart attacks (millions of 2015 dollars)		
Year	Low	Middle	High	Low	Middle	High
Total 1990-2015	9,566	25,216	42,004	21,646	57,060	95,046
2016	302	815	1,390	684	1,844	3,145
2017	291	784	1,339	658	1,774	3,030
2018	276	744	1,273	624	1,684	2,881
2019	258	698	1,197	584	1,581	2,709
2020	238	645	1,108	538	1,459	2,507
2021	213	578	994	482	1,308	2,250
2022	189	514	884	428	1,163	2,001
2023	167	453	780	377	1,025	1,766
2024	147	399	687	332	902	1,554
2025	125	341	587	284	771	1,329
2026	103	281	485	234	636	1,097
2027	81	222	383	184	502	866
2028	57	155	267	129	350	605
2029	28	77	133	64	175	302
Total 2016-2029	2,475	6,706	11,509	5,601	15,174	26,042
Total 1990-2029	12,041	31,922	53,512	27,246	72,234	121,088

Notes: Attributed avoided mortalities based amounts of pollutants abated and COBRA model parameters. Within each block of three columns, Low/Middle/High refers to the scenarios in Table 8-5. Lower values in the left block of Low/Middle/High scenarios are based on low numbers of adult mortality and non-fatal heart attacks in Table 5-8; higher values in the right block are based on high numbers for adult mortality and non-fatal heart attacks. Based on U.S. population in 2017. Totals are not discounted.

8.2 EUL RETURN ON INVESTMENT ANALYSIS

Table 8-7 summarizes monetized energy and resource benefits over the effective useful life of the three technologies. Benefits are discounted back to the beginning of 1976 at 7% and 3%, assuming that each year’s investment cost was incurred at the end of the year.

Table 8-7. Total EUL Energy and Resource Benefits, Summed over the Three Technologies

	Undiscounted (millions of 2015 dollars)			Discounted at 7% (millions of 2015 dollars)			Discounted at 3% (millions of 2015 dollars)		
Year	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
Total 1978-2015	43,819	101,266	161,321	6,540	14,209	22,139	18,315	41,407	65,440
2016	2,826	6,909	11,320	176	431	706	841	2,056	3,369
2017	2,669	6,539	10,731	156	381	626	771	1,890	3,101
2018	2,503	6,147	10,105	136	335	551	702	1,725	2,835
2019	2,316	5,703	9,394	118	291	479	631	1,553	2,559
2020	2,110	5,212	8,606	100	248	410	558	1,378	2,276
2021	1,883	4,657	7,697	84	207	343	483	1,195	1,976
2022	1,666	4,124	6,822	69	172	284	415	1,028	1,700
2023	1,464	3,627	6,004	57	141	233	354	878	1,453
2024	1,281	3,178	5,264	47	115	191	301	747	1,237
2025	1,084	2,691	4,461	37	91	151	247	614	1,018
2026	882	2,195	3,643	28	70	116	195	486	807
2027	687	1,713	2,847	20	51	84	148	368	612
2028	471	1,179	1,962	13	33	54	98	246	410
2029	235	589	980	6	15	25	48	119	199
Total 1978-2029	65,895	155,728	251,158	7,588	16,790	26,393	24,108	55,691	88,990

Notes: These totals include only the dollar-denominated energy and resource benefits. Environmental health benefits are not included.

Table 8-8 summarizes net present values (NPV), benefit-to-cost ratios (BCR), and internal rates of return (IRR) taking into account only EUL energy and resource benefits (based on the benefits summarized in Table 8-7).

Based on EUL energy and resource benefits alone, we estimate that BTO's investments have a NPV of between $7 billion and $26 billion and a benefit-to-cost ratio of between 23-to-1 and 79-to-1 (using a 7% discount rate), and an internal rate of return of between 38% and 51%.

Table 8-8. EUL Investment Performance Metrics: Energy and Resource Benefits

Metric	Low	Mid	High
NPV (millions of 2015 dollars)			
7% Discount Rate	7,252	16,455	26,058
3% Discount Rate	23,613	55,196	88,496
Benefit-to-Cost Ratio			
7% Discount Rate	23:1	50:1	79:1
3% Discount Rate	49:1	113:1	180:1
Internal Rate of Return	38%	46%	51%

Notes: These totals include only the dollar-denominated energy and resource benefits. Environmental health benefits are not included. Benefits associated with residential refrigerators, heat pumps, and central air conditioners include products purchased through 2015, including estimated savings after 2015 during the products' effective useful lives (assumed to be 15 years).

Table 8-9 summarizes total monetized benefits—energy and resource benefits plus environmental health benefits—over the three technologies. Environmental health benefits are based on the lower numbers of adult mortality and non-fatal heart attacks estimated by COBRA. Benefits are discounted back to the beginning of 1976 at 7% and 3%, assuming that each year's investment cost was incurred at the end of the year.

Table 8-9. Total EUL Monetized Benefits, Summed over the Three Technologies

	Undiscounted (millions of 2015 dollars)			Discounted at 7% (mill'ns of 2015 dollars)			Discounted at 3% (millions of 2015 dollars)		
Year	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**	**Low**	**Mid**	**High**
Total 1978-2015	68,430	157,524	250,364	10,033	21,847	34,033	28,528	64,358	101,534
2016	3,364	8,224	13,475	204	499	818	989	2,418	3,963
2017	3,180	7,792	12,788	180	442	725	908	2,225	3,651
2018	2,983	7,326	12,042	158	388	638	827	2,030	3,338
2019	2,759	6,796	11,195	137	337	554	743	1,829	3,012
2020	2,514	6,211	10,256	116	287	475	657	1,623	2,679
2021	2,244	5,549	9,173	97	240	397	569	1,408	2,327
2022	1,985	4,915	8,130	80	199	329	489	1,210	2,002
2023	1,745	4,322	7,155	66	163	270	417	1,033	1,711
2024	1,527	3,787	6,273	54	134	221	354	879	1,456
2025	1,291	3,207	5,317	43	106	175	291	723	1,198
2026	1,051	2,616	4,342	32	81	134	230	572	950
2027	819	2,042	3,393	24	59	98	174	434	721
2028	562	1,405	2,339	15	38	63	116	290	482
2029	280	701	1,168	7	18	29	56	140	234
Total 1978-2029	94,734	222,419	357,408	11,246	24,836	38,959	35,348	81,172	129,257

Notes: These totals include all dollar-denominated benefits: energy and resource benefits plus environmental health benefits. Note that, because environmental health benefits in a given year include internal discounting (reflecting expected numbers of years between pollution emissions and certain adverse health events), discounted values cannot be calculated directly from undiscounted values in this table.

Table 8-10 summarizes net present values (NPV), benefit-to-cost ratios (BCR), and internal rates of return (IRR) taking into account total EUL monetized benefits: energy and resource benefits plus environmental health benefits (based on the benefits summarized in Table 7-3).

With environmental health benefits included, and taking into account the effective useful life of products sold through 2015, we estimate that BTO's investments have a NPV of between $11 billion and $39 billion and a benefit-to-cost ratio of between 34-to-1 and 116-to-1 (using a 7% discount rate), and an internal rate of return of between 46% and 61%.

Table 8-10. EUL Investment Performance Metrics: Energy and Resource Benefits and Environmental Health Benefits

Metric	Low	Mid	High
NPV (millions of 2015 dollars)			
7% Discount Rate	10,911	24,501	38,624
3% Discount Rate	34,854	80,678	128,763
Benefit-to-Cost Ratio			
7% Discount Rate	34:1	74:1	116:1
3% Discount Rate	71:1	164:1	261:1
Internal Rate of Return	46%	55%	61%

Notes: Benefits associated with residential refrigerators, heat pumps, and central air conditioners include products purchased through 2015, including estimated savings after 2015 during the products' effective useful lives (assumed to be 15 years).

9 Summary Results and Conclusions

This section concludes the report by performing some robustness checks (in Sections 9.1 through 9.4) to ensure that our main conclusion—that BTO R&D has been worthwhile—is not sensitive to aspects of our methodology—either in its design (involving various unavoidable assumptions) or in its implementation (namely, the composition of our group of experts). Section 9.5 summarizes some common themes from the qualitative findings in each of the technology chapters, indicating the reasons given by the experts interviewed for why BTO R&D has had the impacts they attributed to it.

The robustness analysis presented in Sections 9.1 through 9.4 will be based on our main estimates of investment performance metrics, reprised here from Section 7 for ease of reference (Table 9-1). For simplicity, we will focus on one performance metric: benefit-to-cost ratio at a 7% discount rate.

Because different sensitivity tests are appropriate for the different technology areas, it will be useful to note that the discounted benefits in the numerator are composed as follows: 16% from flame-retention-head oil burner, 45% from advanced refrigeration, and 39% from heat pump design model and alternative refrigerants research.

Table 9-1. Retrospective Investment Performance Metrics: Energy and Resource Benefits

Metric	Low	Mid	High
NPV (millions of 2015 dollars)			
7% Discount Rate	6,205	13,874	21,804
3% Discount Rate	17,820	40,912	64,945
Benefit-to-Cost Ratio			
7% Discount Rate	20:1	42:1	66:1
3% Discount Rate	37:1	84:1	132:1
Internal Rate of Return	38%	46%	51%

Note: Reprised from Table 7-4. Benefits are retrospective: only energy savings realized through 2015 are included.

9.1 SENSITIVITY TO INCRIMENTAL IMPACT OF FLAME-RETENTION-HEAD OIL BURNER

Recall that we assumed a 16% energy savings for flame-retention-type burners compared to non-flame-retention burners. We based this assumption on field test results (Batey et al., 1978; McDonald et al., 1979 and 1980) and summaries of those results (Butcher et al., 1992; Batey, 2013). Based on these sources, a range of 11% to 22% is generally accepted.

To a first-order approximation, reducing the incremental savings to 11% from 16% gives up roughly one-third of the attributed benefits (i.e., 5/16 = 0.3125). Increasing to 22% increases attributed benefits by roughly 37% (6/16 = 0.375). Calculating the effect of any alternative assumption of the incremental improvement is similarly straightforward.

Because this technology area contributed 16% to our total benefits, the effect of giving up one-third of our benefits in this area would be to reduce our total benefits by roughly 5% (i.e., 0.33×0.16 = 0.053).

9.2 SENSITIVITY TO CHANGES IN THE COMPOSITION OF OUR GROUP OF EXPERTS

To test whether the manner in which our group of experts was constructed could have influenced our results, we regressed the key quantitative data point (impact attribution to BTO) for each respondent on the source of that respondent's name in our sample. We found no significant difference among sources. All regression coefficients were small and not even close to statistically significant. We therefore conclude that a respondent's attribution of impact to BTO R&D does not differ in a statistically significant way depending on whether they were referred to us by DOE, by someone at ORNL, by another respondent, or discovered independently by RTI. This step establishes that our results were probably not significantly affected by our reliance on respondent referrals, which gave us one-third of our interviewees (Table 2-2). In other words, the composition of our sample, in terms of where the contacts came from, is not an important determinant of our average impact estimates.

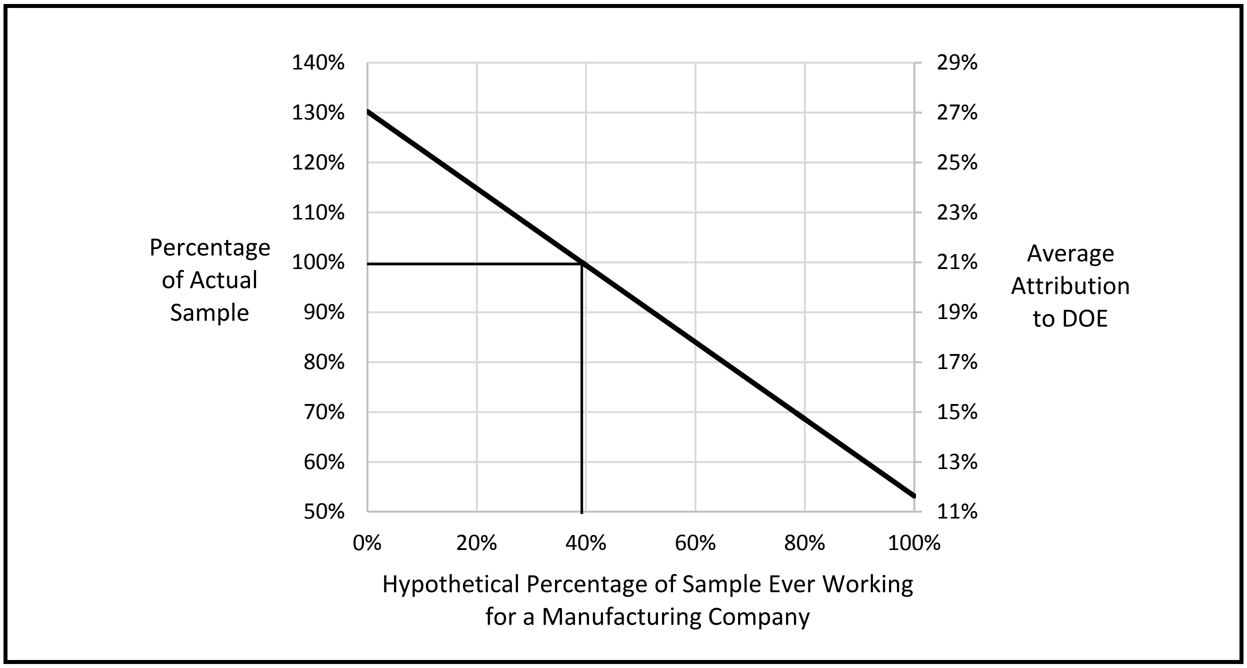
We also regressed BTO impact attribution on other respondent characteristics, including affiliation with a national laboratory, professional involvement in technical R&D efforts, an index of their familiarity with specific BTO R&D activities, and their having ever worked in manufacturing. Only one of these characteristics was found to be significant. That was the respondent's having ever worked for a manufacturing company. Respondents who had worked for a manufacturer (OEM, component, or fluid manufacturing company) tended to attribute lower impact to DOE.

Although it is not sensible to think of a perfect sampling universe with a specific "correct" proportion of such respondents, it is useful to analyze the sensitivity of our results to this proportion. This approach is suggested by Frank et al. (2013) in analogous situations involving observational experiments where the mechanism by which units of observation were exposed to a treatment or not cannot be observed—much as we cannot observe the mechanism by which experts were included in our group.

Figure 9-1 illustrates the sensitivity of the average percentage BTO attribution to hypothetical changes in the composition of our group of experts. If the pattern observed in our group of experts were to stay the same as the percentage of experts who had worked in industry increased, say from just under 40% to just under 80%, then average attribution to BTO would fall from 21% to 15%, and we would lose roughly 30% of our estimated impacts.

Although we cannot characterize the "true" universe of potential experts and assign correct weights to manufacturing respondents, it is helpful to recall that manufacturing respondents made up roughly the same proportion of potential and actual respondents. Recall, from Tables 2-1 and 2-2, that 156 of 397 potential respondents were from industry (39%), and 34 of 91 actual respondents were from industry (37%). In light of this, our example of hypothetically doubling the proportion of manufacturing respondents seems rather extreme. If we were to do this, we would give up roughly a quarter of our total benefits.[39]

Figure 9-1. Sensitivity of Average Attribution to Hypothetical Changes in Sample Composition



Note: Respondents who had worked for a manufacturer tended to attribute lower impact to DOE. The graph shows how average attribution would vary with the composition of the group if this pattern were to stay the same.

9.3 SENSITIVITY TO REBOUND EFFECTS

Improvements in energy performance, by reducing the cost of an energy service, may lead consumers to demand more of that service. Improved fuel efficiency may prompt drivers to drive farther. More efficient water heating technology may encourage people to take longer showers. Improvements in heating and air conditioning efficiency may lead people to turn thermostats up in winter and down in summer. Even improvements in refrigerator energy efficiency may lead to increases in the average size and number of refrigerators in

[39] Recall, advanced refrigeration and HPDM and alternative refrigerants research together contributed 84% percent of total benefits, and 30% of 84% is 25%.

homes. This phenomenon is known as the rebound effect, and it can partially offset the benefits of improvements in energy performance.

Estimates suggest that the rebound effect is unlikely to negate more than 30% of the savings that would otherwise result from a technical improvement in the energy performance of residential heating and air conditioning equipment (Greening et al., 2000; Sorrell, 2007). Evidence for residential refrigeration is thin on the ground, but general consensus is that the effect is much less significant; 10% could be considered an upper bound (Greening et al., 2000; Sorrell, 2007).

Since energy performance improvements in residential heating and air conditioning make up 55% of our overall benefits (16% from flame-retention and 39% from heat pumps and central air conditioners), a 30% rebound effect would take away roughly 16.5% of our overall benefits (i.e. $0.3 \times 0.55 = 0.165$).

Assuming a 10% rebound effect for refrigeration would take away roughly 4.5% overall, since refrigeration contributes 45% of total benefits.

9.4 SCENARIO ANALYSIS

None of the sensitivity analyses suggested can on its own come close to bringing our estimated benefit-to-cost ratios near the unit threshold where we would have to question whether BTO R&D investments have been worthwhile.

A very conservative scenario can be constructed by applying all of these discounts at once:

Flame-retention

- 33% reduction in incremental impact
- 30% reduction because of rebound effect

Refrigeration

- 30% reduction by changing composition of expert group
- 10% reduction because of rebound effect

Heat pump and air conditioning

- 30% reduction by changing composition of expert group
- 30% reduction because of rebound effect

The remaining benefits, as a percentage of the original estimate, can be calculated as follows:

$$(0.16)(1-0.33)(1-0.3)+(0.45)(1-0.3)(1-0.1)$$
$$+(0.39)(1-0.3)(1-0.3)=0.55$$

In this rather extreme scenario, we are still left with more than half of our estimated benefits. Although this reduction is not insignificant, applying this scenario to the lower-bound estimate of a 20-to-1 benefit-to-cost ratio still yields estimated benefits greater than ten times R&D portfolio costs.

9.5 DISCUSSION

We have considered the sensitivity of estimated benefits and investment performance metrics to changes in

- the composition of the group of expert informants with whom we spoke,
- assumptions about the average incremental energy efficiency improvement of flame-retention-head oil burners, and
- assumptions about the magnitude of the rebound effect for all three technology areas.

Scenario analyses show that more than half of estimated benefits remain even under very conservative alternative assumptions. Applying these assumptions to the lower-bound benefits estimates would still result in estimated benefits of more than ten times R&D portfolio costs, strongly supporting the conclusion that BTO investments in HVAC, water heating, and appliance R&D have been worthwhile.

Based on these sensitivity analyses, the main finding is quite robust. Recall, taking the most restrictive estimate of benefits—considering only retrospective benefits for the three technology areas selected from the larger HVAC, water heating, and appliance R&D portfolio and omitting environmental health benefits—we estimated a benefits-to-costs ratio of between 20-to-1 and 66-to-1, with the middle estimate being 42-to-1 (Table 9-1). In an alternative scenario based on the most conservative alternative assumptions considered for the sensitivity analysis (reweighting of expert responses toward a subgroup that gave on average lower attribution to BTO, lower incremental improvement for flame-retention-head oil burners, and rebound effect sizes at the upper end of estimated ranges from peer-reviewed studies), more than half of the estimated benefits remain.

Applying all of these most conservative alternative assumptions to the middle estimate of a 42-to-1 benefit-to-cost ratio still yields an estimate greater than the lower bound of 20-to-1. Applying these assumptions to that lower bound would still leave estimated benefits of more than ten times R&D investment costs, strongly supporting the conclusion that BTO investments in HVAC, water heating, and appliance R&D have been worthwhile.

This conclusion appears all the more robust in light of the following reasons to view the investment performance metrics as conservative lower bounds:

- The portfolio approach, taken here, considers the investment cost of the entire HVAC, water heating, and appliance R&D portfolio from 1976 (including investments made by DOE's predecessor agencies) through 2015, yet includes estimated benefits of only three technology areas within this portfolio.
- The retrospective energy and resource benefits, which are the basis for the top-line investment performance metrics, do not include environmental health benefits or benefits associated with the remaining EUL of equipment operating as of 2015 but due to accrue in 2016 and later.
- Benefits associated with the knowledge generated by BTO R&D, rated as the most important aspect of BTO's contributions by the experts with whom we spoke, are not quantified beyond their effects on energy efficiency of residential refrigerators, heat pumps, and air conditioners. Knowledge benefits are treated only qualitatively, in an analysis of patenting and patent citations.

For these reasons, a benefits-to-costs ratio of 20-to-1 is appropriately viewed as a lower bound on the estimated performance of BTO R&D investments.

Several common themes emerge from the reasons experts offered for why BTO R&D has had the impacts they attributed to it. DOE laboratories are perceived by industry to be a source of credible, objective, scientific and engineering data and fundamental knowledge. The research output of DOE laboratories is valuable to industry because the laboratories combine objectivity—a reputation as a trusted third party—with solid technical capabilities and state-of-the-art facilities, such as HVAC and refrigeration test facilities. DOE laboratories integrate multidisciplinary scientific and engineering capabilities that are beyond the scope of most companies' R&D laboratories. BTO R&D investments are able to leverage these facilities and interdisciplinary expertise to conduct basic research having applications much broader than the scope of any one company's business model. BTO R&D investments can also support early development of novel technologies that companies would find unattractive because of high technical risk (the risk of failing to achieve performance improvements over existing technologies), market risk (the risk of failing to commercialize a product embodying the new technology once it has been successfully developed from a technical perspective), and a long and uncertain timeline to eventual commercialization and market acceptance. Especially high-risk and long-term R&D projects are good candidates for BTO investment because they are less likely to attract private-sector investment.

BTO R&D investments support the role of DOE laboratories as trusted third-party sources of objective, high-quality scientific and engineering data and research. BTO R&D impacts stem from its ability to leverage DOE laboratories' unique capabilities to create productive R&D investment opportunities for the private sector.

BTO R&D can de-risk a new energy-efficient technology to the point that a company will want to invest in its further commercial development. BTO's role in the development of a given technology may vary; depending on the technology, its application, and market and other conditions, BTO involvement may end with basic research or proof of concept, or it may extend through later stages of development. BTO investment is most effective when it complements private investment, i.e., when BTO outputs create productive investment opportunities for the private sector, thereby crowding in private investment. The nature of high-risk R&D portfolios is that not all projects will be successful. In selecting projects, the questions to ask are whether a project is one that BTO is uniquely capable of undertaking—a project which the private sector could not or would not choose to undertake—and whether, if it is technically successful, the project will create productive investment opportunities for U.S. industry while advancing BTO's mission.

10 References

Abdelaziz, O., Shrestha, S.,…, and Kassuga, T. (2015). *Alternative Refrigerant Evaluation for High-Ambient-Temperature Environments: R-22 and R-410A Alternatives for Mini-Split Air Conditioners*. ORNL/TM-2016/513.

Abdelaziz, O., Shrestha, S.,…, and Bargach, Y. (2016). *Alternative Refrigerant Evaluation for High-Ambient-Temperature Environments: R-22 and R-410A Alternatives for Rooftop Air Conditioners*. ORNL/TM-2015/536.

Air-Conditioning, Heating, and Refrigeration Institute [AHRI]. (2017). *Historical Data: Central Air Conditioners and Air-Source Heat Pumps.* http://www.ahrinet.org/Resources/Statistics/Historical-Data/Central-Air-Conditioners-and-Air-Source-Heat-Pumps.aspx. Accessed 5/18/17.

Association of Home Appliance Manufacturers (2013). Refrigerators (6.5 cu.ft. or greater). Factory Shipments (Including Exports).

Batey, J. E. (2013). *Present and Future Energy Efficiency Upgrade and Conservation Opportunities for Residential Oil Heating in New York State*, prepared for Empire State Petroleum Association, Inc.

Batey, J. E., Allen, T. W., McDonald, R. J., Hoppe, R. J., Salzano, F. J., & Berlad, A. L. (1978). *Direct Measurement of the Overall Efficiency and Annual Fuel Consumption of Residential Oil-Fired Boilers, Annual Report, Fiscal Year 1977, Burner-Boiler/Furnace Efficiency Test Project* (No. BNL 50853). Brookhaven National Lab., Upton, NY (United States).

Baxter, V. D., Khowailed, G., Sikes, K., & Grubbs, T. (2015). Space Cooling in North America: Market Overview and Future Impacts. *IEA Heat Pump Center Newsletter* (Online), 32(2).

Brown, M. A., Berry, L. G., & Goel, R. K. (1989). *Commercializing government-sponsored innovations: twelve successful buildings case studies* (No. ORNL/CON-275). Oak Ridge National Lab., TN (United States).

Butcher, T., McDonald, R., Krajewski, R., Celebi, Y., & Andrews, J. (1992). *Impacts of changing residential oil burner technology* (No. BNL-47615; CONF-920828--3). Brookhaven National Lab., Upton, NY (United States).

Cohen, W. M., Nelson, R. R., & Walsh, J. P. (2000). Protecting their intellectual assets: Appropriability conditions and why US manufacturing firms patent (or not). NBER Working Paper no. 7552.

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

U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy. (2002, March). Strategic Program Review. Accessed 6/29/2017 at https://energy.gov/sites/prod/files/2013/11/f5/strategic_program_review.pdf.

U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy, Building Technologies Office. (2017). R&D to Market Success: BTO-Supported Technologies Commercialized from 2010 to 2015. Accessed at https://energy.gov/eere/buildings/downloads/rd-market-success-bto-supported-technologies-commercialized-2010-2015.

U.S. Energy Information Administration (EIA). (2011, September). Annual Energy Review 2011. DOE/EIA-0384(2011). Accessed at https://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf.

U.S. Energy Information Administration (EIA). (2016a). U.S. Sales of Distillate Fuel Oil by End Use. Accessed at http://www.eia.gov/dnav/pet/pet_cons_821dst_dcu_nus_a.htm.

U.S. Energy Information Administration (EIA). (2016b). Weekly U.S. No. 2 Heating Oil Residential Price (Dollars per Gallon). Accessed at http://tonto.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=W_EPD2F_PRS_NUS_DPG&f=W.

U.S. Energy Information Administration (EIA). (2016c). Annual U.S. Crude Oil First Purchase Price (Dollars per Barrel). Accessed at http://tonto.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=F000000__3&f=A.

U.S. Energy Information Administration (EIA). (2017a). Petroleum Supply Monthly, preliminary data for 2016. https://www.eia.gov/energyexplained/index.cfm?page=oil_refining. Last accessed 5/19/2017.

U.S. Energy Information Administration (EIA). (2017b). Supply and Disposition of Petroleum and Other Liquids. https://www.eia.gov/dnav/pet/pet_sum_snd_d_nus_mbbl_a_cur.htm. Last accessed 5/21/2017.

U.S. Energy Information Administration (EIA). (2017c). Net generation by electric power utilities. https://www.eia.gov/electricity/data.php#generation. Last accessed 5/21/2017.

U.S. Environmental Protection Agency (EPA). (2014). Co-Benefits Risk Assessment (COBRA) Screening Model: How COBRA Works. Accessed 6/29/2017 from https://www.epa.gov/sites/production/files/2015-11/documents/how-cobra-works.pdf.

U.S. Environmental Protection Agency (U.S. EPA). (2015). *User's manual for the Co-Benefits Risk Assessment (COBRA) screening model*. Accessed 6/29/2017 from https://19january2017snapshot.epa.gov/sites/production/files/2015-08/documents/cobra-manual.pdf.

U.S. Environmental Protection Agency (EPA). (2017a). AP-42: Compilation of Air Emission Factors. https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emission-factors. Last accessed 5/21/2017. And https://www3.epa.gov/ttnchie1/ap42/ch01/final/c01s03.pdf. Last accessed 5/21/2017.

U.S. Environmental Protection Agency (EPA). (2017b). Air Pollutant Emissions Trends Data. Average Annual Emissions. Criteria pollutants National Tier 1 for 1970 - 2016. https://www.epa.gov/air-emissions-inventories/air-pollutant-emissions-trends-data. Last accessed 5/21/2017.

Energy Star (2013). *Air Source Heat Pump Savings Calculator*. https://www.energystar.gov/buildings /sites/default/uploads/files/ASHP_Sav_Calc.xls. Last accessed 5/18/2017.

Feller, I. (2017) Assessing the societal impact of publicly funded research. *The Journal of Technology Transfer*, 1-19.

Frank, K. A., Maroulis, S. J., Duong, M. Q., and Kelcey, B. M. (2013). What would it take to change an inference? Using Rubin's causal model to interpret the robustness of causal inferences. *Educational Evaluation and Policy Analysis*, 35(4), 437-460.

General Accounting Office (GAO). (1996). DOE's Success Stories Report. Washington, D.C. GAO/RCED-96-120R. Accessed 6/29/2017 at http://www.gao.gov/assets/90/85442.pdf.

Greening, L. A., Greene, D. L., and Difiglio, C. (2000). Energy efficiency and consumption—the rebound effect—a survey. *Energy policy*, 28(6), 389-401.

Griliches, Z. (1958). Research costs and social returns: Hybrid corn and related innovations. *Journal of Political Economy, 66*, 419–431.

Haneke, B. H. (2001). A national methodology and emission inventory for residential fuel combustion. https://www3.epa.gov/ttnchie1/conference/ei12/area/haneke.pdf. Last accessed 5/21/2017.

Krewski, D., Jerrett, M., Burnett, R. T., Ma, R., Hughes, E., Shi, Y., Turner, M. C., … Tempalski, B. (2009). Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality. *Research Report of the Health Effects Institute,* 140, 5–114; discussion 115-136.

Laden, F., Schwartz, J., Speizer, F. E., and Dockery, D. W. (2006). Reduction in fine particulate air pollution and mortality: Extended follow-up of the Harvard Six Cities Study. *American Journal of Respiratory and Critical Care Medicine,* 173(6), 667–672.

Link, A. N., and Scherer, F. M. (Eds.). (2005). *Essays in Honor of Edwin Mansfield: The Economics of R&D, Innovation, and Technological Change*. Springer Science & Business Media.

Link, A. N. & Scott, J. T. (2010). *Public goods, public gains: Calculating the social benefits of public R&D*. New York: Oxford University Press.

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, 221–240.

Mar, T. F., Larson, T. V., Stier, R. A., Claiborn, C., and Koenig, J. Q. (2004). An analysis of the association between respiratory symptoms in subjects with asthma and daily air pollution in Spokane, Washington. *Inhalation Toxicology,* 16(13), 809–815.

McDonald, R. J., Batey, J. E., Allen, T. W., & Hoppe, R. J. (1979). *Direct Efficiency Measurement and Analysis of Residential Oil-Fired Boiler Systems* (No. BNL 51171). Brookhaven National Lab., Upton, NY (United States).

McDonald, R. J., & Krajewski, R. F. (1980). *Flame-retention head burner efficiency test results and analysis. Space-heating-equipment test program* (No. BNL-51321). Brookhaven National Lab., Upton, NY (United States).

McMahon, J. E., Chan, P., and Chaitkin, S. (2001). Impacts of US appliance standards to date. In *Energy efficiency in household appliances and lighting* (pp. 547-559). Springer, Berlin, Heidelberg.

Meyers, S., McMahon, J. E., McNeil, M., and Liu, X. (2003). Impacts of US federal energy efficiency standards for residential appliances. *Energy*, 28(8), 755-767.

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(Supplement 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* (pp. 183–198). Boston, MA: Health Effects Institute.

National Research Council. (2001). *Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000.* National Academies Press.

Nemtzow (2001). Testimony of David M. Nemtzow, President of the Alliance to Save Energy, before the Senate Environment and Public Works Committee, Subcommittee on Clean Air, Wetlands, Private Property, and Nuclear Safety, Hearing on Energy and the Environment, March 21, 2001. Accessed 6/29/2017 at https://www.epw.senate.gov/107th/nem_0321.htm.

Newell, R. G., Jaffe, A. B., and Stavins, R. N. (1999). The induced innovation hypothesis and energy-saving technological change. *The Quarterly Journal of Economics*, 114(3), 941-975.

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

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

Ostro, B., Lipsett, M., Mann, J., Braxton-Owens, H., and White, M. (2001). Air pollution and exacerbation of asthma in African-American children in Los Angeles. *Epidemiology,* 12(2), 200–208.

Peters, A., Dockery, D. W., Muller, J. E., and Mittleman, M. A. (2001). Increased particulate air pollution and the triggering of myocardial infarction. *Circulation,* 103(23), 2810–2815.

Petroleum Marketers Association of Ammerica (PMAA) (1988). Statement of C. Richard Cahoon, Vice President for Policy, before the Subcommittee on Energy Research and Development, Committee on Science, Space, and Technology, U.S. House of Representatives, March 10, 1988, Washington, D.C. Accessed 6/29/2017 at http://digitalcollections.library.cmu.edu/awweb/awarchive?type=file&item=440315.

Pope, C. A., Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., and Thurston, G. D. (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA,* 287(9), 1132–1141.

Popp, D., Newell, R. G., and Jaffe, A. B. (2010). Energy, the environment, and technological change. In Bronwyn H. Hall and Nathan Rosenberg: *Handbook of the Economics of Innovation*, Volume 2, , 873-937.

Porter, M. E., and Van der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. *The journal of economic perspectives*, 9(4), 97-118.

Ruegg, R., O'Connor, A.C., & Loomis, R.J., (2014). *Evaluating Realized Impacts of DOE/EERE R&D Programs: Standard Impact Evaluation Method*.

Scherer, F. M., and Harhoff, D. (2000). Technology policy for a world of skew-distributed outcomes. *Research policy*, 29(4), 559-566.

Shedlick, M., Link, A., and Scott, J. (1998). *Economic assessment of the NIST alternative refrigerants research program*. NIST Planning Report, 98-1. Accessed at https://www.nist.gov/sites/default/files/documents/2017/05/09/report98-1.pdf.

Sorrell, S. (2007). *The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency*. Sussex Energy Group for the Technology and Policy Assessment function of the UK Energy Research Centre.

Woodruff, T. J., Grillo, J., and Schoendorf, K. C. (1997). The relationship between selected causes of postneonatal infant mortality and particulate air pollution in the United States. *Environmental Health Perspectives,* 105(6), 608–612.

Appendix A: Interview Guides

ADVANCED REFRIGERATION INTERVIEW GUIDE

Interview Guide: DOE/EERE Building Technologies Office Economic Impact Study
Advanced Refrigeration Research

The U.S. Department of Energy has contracted with RTI International to study the impact of Building Technologies Office research and development (R&D) investments and ancillary activities. This survey looks specifically at the impact of the Advanced Refrigeration R&D activities supported by DOE.

Your perspective will help guide DOE's planning and investment process. Participation in this study is confidential; only aggregated information will be included in any deliverables or communications. Your name and your company's/organization's name will not be disclosed.

Our research products will be an economic analysis, final report, and presentation materials. All deliverables will be publicly available in late summer 2017, and these will be shared with you as soon as they are released.

Throughout the survey, we will be seeking both qualitative and quantitative information. Quantitative information may be rough approximations based on your experience, but this data is important for us to aggregate the responses of all the survey participants in a meaningful way.

If you have questions, please contact:

- Troy Scott, RTI Project Manager, 503-428-5680 or tjscott@rti.org
- Zack Oliver, Data Collection Lead, 919-541-8911 or zoliver@rti.org
- Antonio Bouza, DOE Project Officer, 202-586-4563 or Antonio.Bouza@ee.doe.gov
- John Mayernik, Evaluation Advisor, 202-448-2209 or John.Mayernik@nrel.gov

Background on Advanced Refrigeration Technology

Figure 1 below lists DOE research activities along with other activities that were happening during the same time frame. Figure 2 displays these activities on a visual timeline. We will ask about the impact of DOE funded activities on private sector R&D costs, product costs, and performance, among other things. Figure 3a and Figure 3b show sales-weighted average efficiency of residential refrigerators along with the timing of state and federal efficiency standards.

Figure 1: Factors Influencing Refrigeration Efficiency in the U.S.

- Department of Energy (DOE)
  - 1981: Development of a more efficient compressor by Columbus Products engineers, under subcontract to ORNL. Design changes to the motor, suction muffler, and compressor valve assembly achieved a 44% reduction in energy use.
  - 1993-1998: Under a CRADA with the Appliance Industry-Government CFC Replacement Consortium (a subsidiary of Association of Home Appliance Manufacturers [AHAM]), engineers from ORNL and industry explored new technical options to improve refrigerator energy efficiency using non-CFC refrigerants.
  - 1982: Multiple unequal parallel compressors, now the industry standard, can be traced to R&D at ORNL that demonstrated potential energy savings of 15% to 26%.
  - 1984: Collaboration between ORNL and Foster-Miller Associates, H. E. Butt Grocery, and Friedrich Commercial Refrigeration led to the commercialization of an advanced supermarket refrigeration system, which by the late 1990s was used by about 80% of supermarkets.
  - 1991: Under a CRADA with Lockheed Martin Energy Research and the Appliance Research Consortium, DOE funded the development and testing of a 1 kWh/day refrigerator-freezer, which represented a 50% reduction compared with the 1993 NAECA standard for 20 ft3 units. The final prototype achieved an energy consumption level of 0.93 kWh/day.
  - 2001: The development, with National Energy Technology Laboratory (NETL), A.D. Little, and Delfield, of a commercial refrigerator.
- State and Federal Efficiency standards
  - CA state standards (1978, 1980)
  - Federal efficiency standards (1990, 1993, 2001)
- Environmental standards
  - 1996: CFC phase out schedule established by the Montreal Protocol
- Utility led-initiatives
  - Incentives/rebates for customers to purchase more efficient models
  - 1993: The Super-Efficient Refrigerator Program (SERP) which awarded $30 million to the refrigerator manufacturer that developed and commercialized a refrigerator that exceeded 1993 federal efficiency standards by at least 25%
- Industry
  - Mid-1970s: Manufacturers switched from manually installed fiberglass insulation to robotically blown polyurethane foam installation which improved product quality and was more energy efficiency.
- Other
  - 1979: EnergyGuide appliance labeling rules established by the FTC
- External factors such as the oil price shocks of 1973 and 1979 and real electricity prices peaking in 1982-83

Figure 2: Timing of Policies, Ongoing Events, and Standards

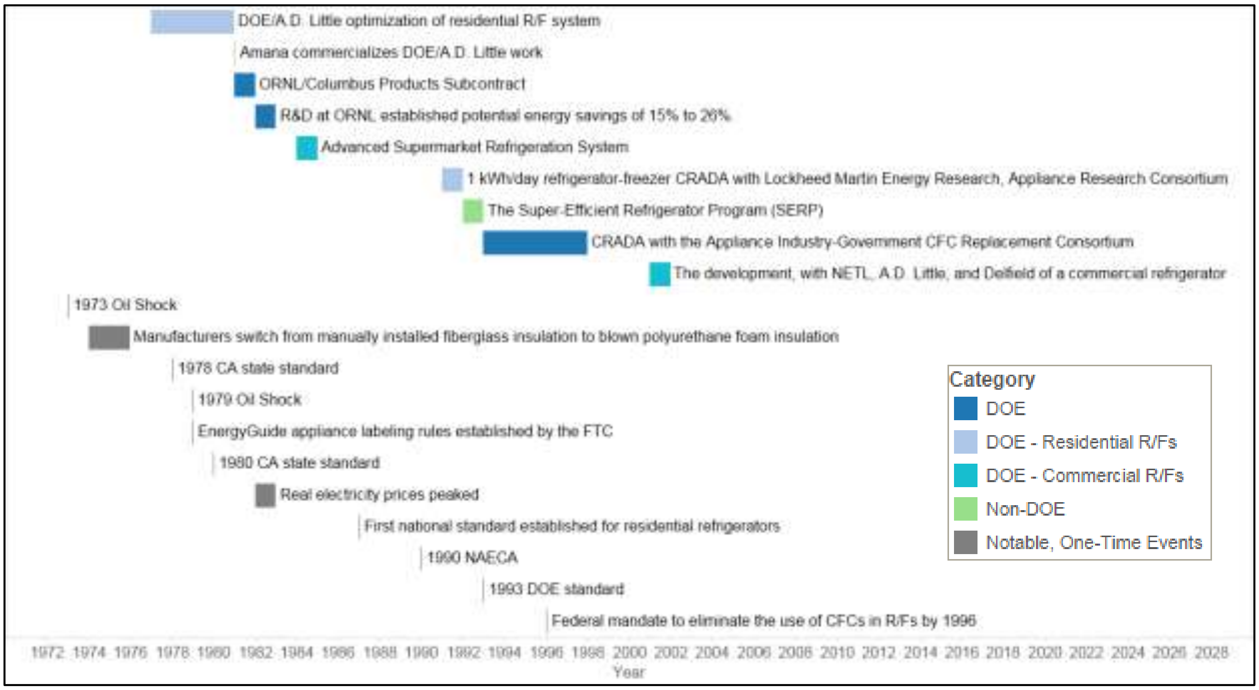


Figure 3 – Average Energy Use per Unit per Year

Figure 3a – 1947 to 2001

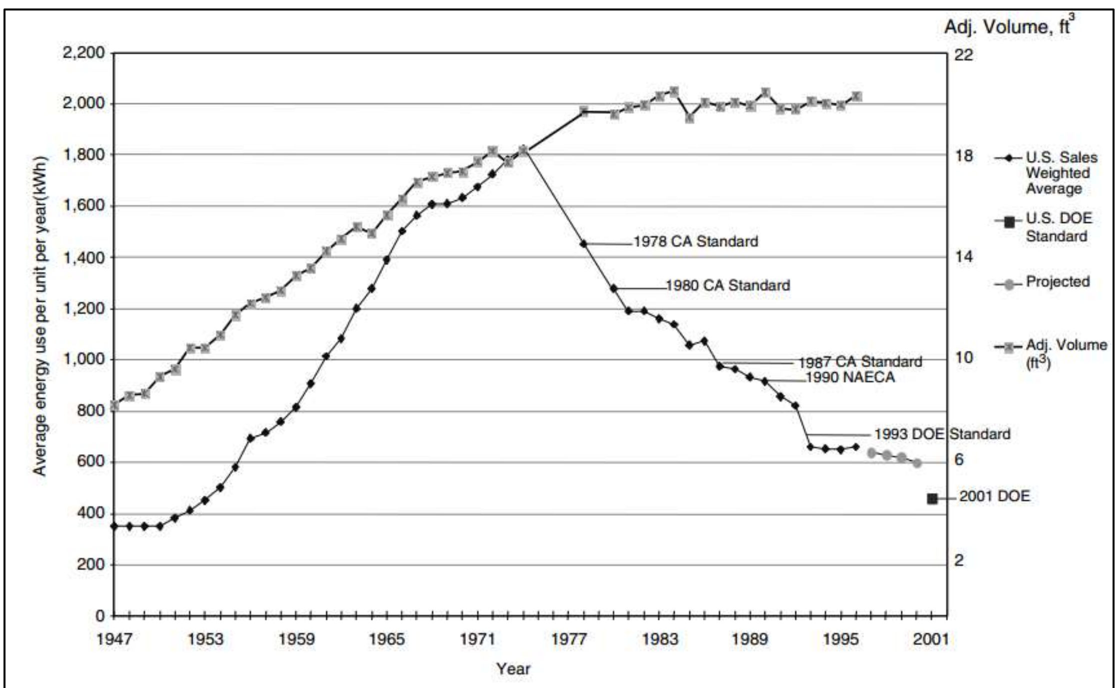
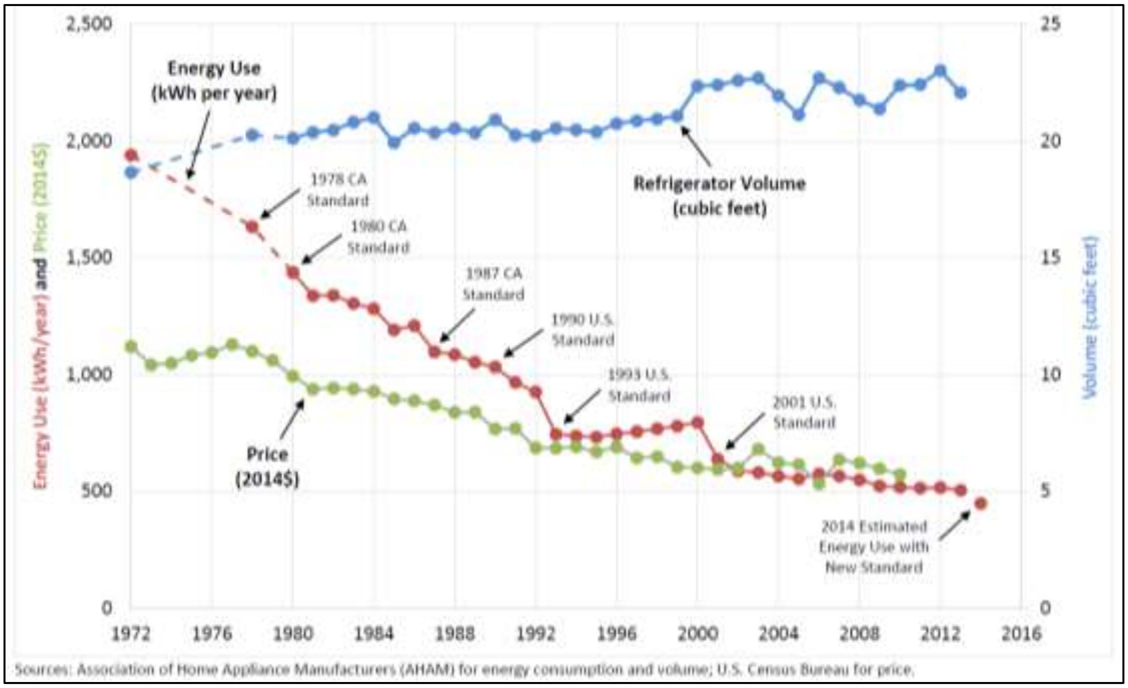


FIGURE E-1 Electricity consumed by refrigerators, 1947 to 2001. SOURCE: Goldstein and Geller, 1998.

Source: National Academy of Sciences. 2001. "Energy Research at DOE: Was It Worth It? Energy Efficiency and Fossil Energy Research 1978 to 2000."

Figure 3b – 1972 to 2014



Source: Appliance Standards Awareness Project, 2015

SECTION I. Respondent Background

1. Which of the following best describes your background in relation to advanced refrigeration research & development? *Check all that apply.*
   ☐ Worked for a manufacturer that conducted research/testing/other technical efforts
      __ Refrigerator manufacturer
      __ Other: ______________________
   ☐ Led public-private collaboration on technical efforts
   ☐ Participated in public-private collaboration on technical efforts
   ☐ Led industry-only technical efforts for a manufacturer
   ☐ Participated in industry-only technical efforts
   ☐ Employed in a federal agency or research lab
   ☐ Employed in a state energy office
   ☐ Worked for a trade association
   ☐ Worked for a university or research institute
   ☐ Worked for an electric utility
   ☐ Other: ______________________________

   Please give a brief description of your background:

2. Were you involved in or familiar with any of the following programs/activities related to advanced refrigeration? *Check all that apply.*

	Directly Involved	Very Familiar	Somewhat Familiar
▪ Development of a compressor by Columbus Products, under subcontract to ORNL	☐	☐	☐
▪ R&D at ORNL on multiple unequal parallel compressors	☐	☐	☐
▪ Collaboration on an advanced supermarket refrigeration system between ORNL and Foster-Miller Associates, H. E. Butt Grocery, and Friedrich Commercial Refrigeration	☐	☐	☐
▪ Development of a commercial refrigerator with National Energy Technology Laboratory, A.D. Little, and Delfield	☐	☐	☐
▪ CRADA with the Appliance Industry-Government CFC Replacement Consortium	☐	☐	☐
▪ Other	☐	☐	☐

Please give a brief description:

3. Have you ever received DOE funding for your work or participated in collaborative R&D activities with a DOE-funded laboratory such as Oak Ridge National Laboratory or the National Energy Technology Laboratory?
   ☐ No
   ☐ Yes. Please give a brief description:

4. Have you been involved in commercial R&D related to refrigeration in the past 15 years?
   ☐ No (please skip down to Section III)
   ☐ Yes

SECTION II. This next set of questions pertains to DOE's involvement in and impact on the research and development activities related to advanced refrigeration technology that you were involved in. We will be asking you to quantify these impacts to the best of your ability.

Ask these questions if the respondent answered Yes to Question 4.

We are trying to isolate the impact of DOE R&D investments and activities as much as possible, and this poses some challenges. For example, efficiency standards affect companies' incentives to perform R&D and commercialize more efficient refrigeration systems, and the DOE R&D activities we are focused on have indirect effects on the evolution of standards. Similarly, EnergyGuide labeling, ENERGY STAR qualification and rebates rely on test methods linked to DOE R&D activities.

Therefore, if we were to hold fixed the exact timeline of these factors (for instance, the timing of updates to standards) we would be assuming away a part of the impact we are trying to estimate. What we would like to try to do instead is to think about holding constant the environment—the institutional frameworks—in which standards, labeling, and subsidies evolve, and consider what would happen without the DOE R&D-related activities and investments described in Question 5:

5. In what ways has your R&D work on refrigeration been influenced by DOE?

   Provide a number from 0 to 3 (0 = DOE did not contribute in this way; 1 = minimal DOE contribution; 2 = moderate DOE contribution; 3 = major DOE contribution).

   _____Through DOE's contributions to the knowledge base on which R&D work drew (e.g., formal science literature, conference presentations and discussions, patents, knowledge and training of yourself and your colleagues)

   _____Through access to scientific and engineering data produced by DOE laboratories

   _____Through the licensing/transfer of technology that DOE helped to develop

   _____Through consultations with DOE scientists and engineers

   _____Through access to DOE laboratory facilities

   _____Through equipment/component testing performed at DOE laboratories

   _____Through direct R&D funding from DOE

   _____Other: ________________________________

   ☐ DOE had no influence (please skip down to question 8)

   Please give a brief description of DOE influences:

6. Would your R&D work on refrigeration have been undertaken without the DOE factors identified above? (please select the most likely scenario)

   ☐ The work would not have been undertaken

   ☐ At least some of the work would still have been undertaken, but the effort levels, costs, timelines, and/or outcomes would have been different

   ☐ The work would still have been undertaken, without significant difference in effort levels, costs, timelines, or outcomes (please skip down to question 8)

Please give a brief description of how effort levels, costs, timelines, and/or outcomes would have been different (or why the work would not have been undertaken). (Note: If the work would not have been undertaken at all, please skip down to question 8):

7. Without the DOE factors identified above:

☐ The level of effort, in terms of research personnel years, would have been

_____________ research personnel years [☐ MORE ☐ LESS] (a range is fine).

OR ______________ % [☐ MORE ☐ LESS] (a range is fine).

☐ The cost of the work would have been

$_____________ x1000 $ [☐ MORE ☐ LESS] (a range is fine).

OR ______________ % [☐ MORE ☐ LESS] (a range is fine).

☐ To reach the same outcomes (in terms of energy efficiency and other performance attributes) would have taken

________________ calendar years [☐ MORE ☐ LESS] (a range is fine).

OR ______________ % [☐ MORE ☐ LESS] (a range is fine).

If any of the DOE factors identified in question 5 were especially important for one or more of these impacts, please give a short explanation:

8. What were the technical outcomes of your R&D work? Where possible, please provide the baseline parameter and improved parameter (e.g., pre and post energy efficiency, or pre and post equipment cost).

☐ Improvements in energy efficiency

Please describe:

☐ Improvements in other performance attributes

Please describe:

☐ Improvements in equipment cost for which these levels of energy efficiency or other performance attributes could be achieved

Please describe and include cost savings:

9. If DOE factors identified above had any impact on these outcomes, what was the DOE effect in terms of the proportion of the improvements you view were attributable to DOE activities?

Improvements in Energy Efficiency	**Improvements in performance attributes**	**Improvements in equipment costs**
☐ Less than 10%	☐ Less than 10%	☐ Less than 10%
☐ Between 10-24%	☐ Between 10-24%	☐ Between 10-24%
☐ Between 25-49%	☐ Between 25-49%	☐ Between 25-49%
☐ Between 50-75%	☐ Between 50-75%	☐ Between 50-75%
☐ Greater than 75%	☐ Greater than 75%	☐ Greater than 75%

Please give a short explanation of your reasoning. Please note if any of the DOE factors checked above were especially important for one or more of these impacts:

10. Was a new product commercialized as a result of this R&D work?
    - ☐ No (please skip down to Section III)
    - ☐ Yes

11. Without the DOE factors identified in question 5, taking into account the impacts on energy efficiency, other performance attributes, and equipment cost described above:
    a. How likely is it that your company would have commercialized the product in the same time frame (please select one)?
       - ☐ No chance the product would have been commercialized.
       - ☐ 0% to 25% chance
       - ☐ 25% to 50% chance
       - ☐ 50% to 75% chance
       - ☐ 75% to 100% chance
       - ☐ The product would have been commercialized in the same time frame without the DOE factors identified above.

    b. If your company had commercialized the product without the DOE factors identified above, how would its sales volume today compare with that of the product actually commercialized?
       - ☐ No difference in sales (i.e., any difference in price, energy efficiency, and performance attributes would have negligible effect on sales)
       - ☐ Sales would have been lower by roughly _________% (a range is fine).
       - ☐ Sales would have been higher by roughly_________% (a range is fine).

    Please give a short explanation of your reasoning:

(Respondents answering Section II questions skip to Section IV)

SECTION III. This next set of questions pertains to your opinion of DOE's influence on the market and industry trends for refrigeration systems in general.

We are trying to isolate the impact of DOE R&D investments and activities as much as possible, and this poses some challenges. For example, efficiency standards affect companies' incentives to perform R&D and commercialize more efficient refrigeration systems, and the DOE R&D activities we are focused on have indirect effects on the evolution of standards. Similarly, EnergyGuide labeling, ENERGY STAR qualification and rebates rely on test methods linked to DOE R&D activities.

Therefore, if we were to hold fixed the exact timeline of these factors (for instance, the timing of updates to standards) we would be assuming away a part of the impact we are trying to estimate. What we would like to try to do instead is to think about holding constant the environment—the institutional frameworks—in which standards, labeling, and subsidies evolve, and consider what would happen without the DOE R&D-related activities and investments described in Question 12:

12. How did DOE impact the commercial R&D (performed in the last 15 years) necessary for companies to bring more energy-efficient refrigeration systems to market?

    Provide a number from 0 to 3 (0 = DOE did not contribute in this way; 1 = minimal DOE contribution; 2 = moderate DOE contribution; 3 = major DOE contribution).

    _____Through DOE's contributions to the knowledge base on which R&D work drew (e.g., formal science literature, conference presentations and discussions, patents, knowledge and training of yourself and your colleagues)

    _____Through access to scientific and engineering data produced by DOE laboratories

    _____Through the licensing/transfer of technology that DOE helped to develop

    _____Through consultations with DOE scientists and engineers

    _____Through access to DOE laboratory facilities

    _____Through equipment/component testing performed at DOE laboratories

    _____Through direct R&D funding from DOE

    _____Other: ________________________________

    _____DOE had no influence (please skip down to question 15)

    Please give a brief description of DOE influences:

13. Without the DOE impacts discussed in Question 12, would the commercial R&D necessary to bring more energy-efficient refrigeration systems to market still have been undertaken within the same time frame?

    ☐ The commercial R&D would not have been undertaken.

    ☐ At least some of the commercial R&D would still have been undertaken, but the effort levels, costs, timelines, and/or outcomes would have been different.

    ☐ The commercial R&D would still have been undertaken, without significant difference in effort levels, costs, timelines, or outcomes.

    Please give a brief explanation:

14. Given your answers to Question 13, how would the market for refrigeration systems look different than it does today without the DOE impacts discussed above?

    ☐ Average energy use would be: ☐ higher
    ☐ lower
    by roughly _____________ %.

    ☐ Average price would be: ☐ higher
    ☐ lower
    by roughly _____________ %.

    ☐ Average sales volume would be: ☐ higher
    ☐ lower
    by roughly _____________ %.

    ☐ There would be no difference (the market would be exactly as it is today).

    Please give a brief explanation:

Section IV. Additional Comments

15. Are there any additional comments you would like to share?

Respondent Contact Information (optional)
Name: ____
Title: ____
Division: ____
Company/Organization: ____
Location, if not USA: ____

Would you be willing to be contacted for a brief follow-up discussion of your responses to this survey?
☐ Yes, by phone _______________________
☐ Yes, by email _______________________
☐ No

THANK YOU for contributing your time and insight to the study.

HEAT PUMP DESIGN MODEL RESEARCH INTERVIEW GUIDE

Interview Guide: DOE/EERE Building Technologies Office Economic Impact Study Alternative Refrigerants and Heat Pump Design Model Research

The U.S. Department of Energy (DOE) has contracted with RTI International to study the impact of Building Technologies Office (BTO) research and development investments and ancillary activities. This survey looks at the impact of U.S. government R&D activities, and specifically at the impact of DOE's R&D efforts, on the energy performance of air conditioners and heat pumps. Two major technological contributions enabling the improvements in energy performance were the Heat Pump Design Model (HPDM) developed and maintained by Oak Ridge National Laboratory (ORNL) and the DOE and other government agencies' (EPA, NIST) research on alternative refrigerants that supported industry in successfully phasing out chlorofluorocarbons (CFCs) in accordance with the Montreal Protocol.
Your perspective will help guide DOE's planning and investment process. Participation in this study is confidential; only aggregated information will be included in any deliverables or communications. Your name and your company's/organization's name will not be disclosed.

Our research products will be an economic analysis, final report, and presentation materials. All deliverables will be publicly available in late summer 2017, and these will be shared with you as soon as they are released.

If you have questions, please contact:

- Michael Gallaher, RTI Project Director, 919-541-5935 or mpg@rti.org
- Troy Scott, RTI Project Manager, 503-428-5680 or tjscott@rti.org
- Antonio Bouza, DOE Project Officer, 202-586-4563 or Antonio.Bouza@ee.doe.gov
- John Mayernik, Evaluation Advisor, 202-448-2209 or John.Mayernik@nrel.gov

Background on Alternative Refrigerants and Heat Pump Design Model

Over the past 15 years the average efficiency of air conditioners and heat pumps has almost doubled. Federal Minimum Energy Performance Standards (MEPS) rose from about 9.5 SEER in 1990 to over 15 SEER today. These trends, as depicted in Figure 1, were influenced by a wide range of public and private sector investments and activities which included DOE and other major government research activities.

Since 1981, DOE has conducted and funded technical research that played a key role in the industry-wide phaseout of CFCs—an ozone-depleting greenhouse gas commonly used in refrigerants—from refrigerators, air conditioners, and other applications. Major DOE activities include the following:

- Mixed Refrigerants Research (1981–1992)
- Generic Research on New Refrigerants (1986–1992)
- Alternative Fluorocarbons Environmental Acceptability Study (AFEAS) Collaborative R&D Agreement (1989–1997)
- Materials Compatibility and Lubricants Research (MCLR) Program (1991–1999)

DOE also developed the Heat Pump Design Model (HPDM) which been used by ORNL and industry (often in collaboration) to develop next-generation products. The HPDM also played a part in transitioning to non-CFC refrigerants, modeling system design modifications that were needed to accommodate and optimize for the new fluids.

Figure 1 shows the trend in U.S. shipment-weighted average SEER of air conditioners and heat pumps since 1990.

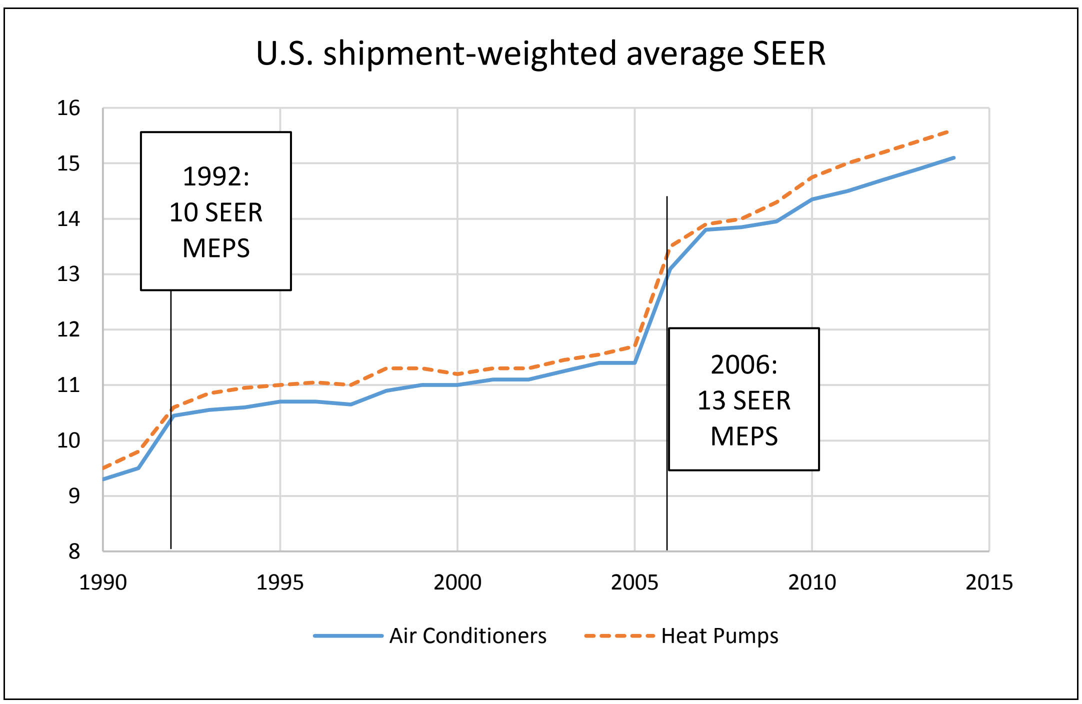


Figure 1. U.S. shipment-weighted average SEER.

Research activities that were happening during the development of the HPDM and Alternative Refrigerants. Some major milestones include:

- 1982-1991: Mixed Refrigerants Research – DOE investigated the heat transfer characteristics and the system performance, design, and operability of zeotropic refrigerant mixture.
- 1986-1992: ORNL conducts generic research on CFC alternative refrigerants resulted in a public domain performance data from an experimental vapor compression cycle system. DOE also funded the National Institute for Standards and Technology (NIST) [1982-1986] to evaluate the availability of thermophysical properties of alternative refrigerants and develop consensus property formulations internationally.
- 1988: ORNL updates the HPDM to model variable-speed designs.
- 1989-1997: DOE contributes major role to the Alternative Fluorocarbons Environmental Acceptability Study (AFEAS) CRADA established by 17 of the world's Chemical companies. DOE tested alternatives to CFC refrigerants for their environmental, health, and safety characteristics. DOE/ORNL developed the Total Equivalent Warming Impact (TEWI) metric.
- 1991-1999: DOE funds and participates in the Materials Compatibility and Lubricants Research (MCLR) Program, researching refrigerant and lubricant properties and related system design issues.
- 1992: DOE establishes Minimum Energy Performance Standards (MEPS) of 10 SEER for both air conditioners and heat pumps.
- Driven by the Montreal Protocol, DOE, NIST, EPA and industry conduct R&D to develop alternative (non CFC) refrigerants.
- ASHRAE, AHRI and other research organizations contribution to the knowledge base.
- 1995: ORNL updates the HPDM to model non-chlorinated refrigerant mixtures.
- 2006: DOE establishes Minimum Energy Performance Standards (MEPS) of 13 SEER for both air conditioners and heat pumps.
- Financial incentives were provided by electric utilities for installing energy-efficient equipment.

Section I. The first set of questions pertains to your background and involvement in the development or use of the heat pump design model, efficiency improvements in vapor-compression equipment, and/or development of CFC alternative refrigerants.

==

Respondent Background

1. Please give a brief description of your background in relation to the HPDM, efficiency improvements in vapor-compression equipment and/or alternative refrigerants research:

2. If your background involves research/development/testing/other technical/engineering efforts, on which of the following types of vapor compression equipment have you worked?
   ☐ Heat pump equipment
   ☐ Worked for a manufacturer that conducted research/testing/other technical efforts
      __ Refrigerant manufacturer
      __ HVAC equipment manufacturer
      __ Other: ______________________
   ☐ Led public-private collaboration on technical efforts
   ☐ Participated in public-private collaboration on technical efforts
   ☐ Led industry-only technical efforts
   ☐ Participated in industry-only technical efforts
   ☐ Employed in a federal agency or research lab
   ☐ Employed in a state energy office
   ☐ Worked for a trade association
   ☐ Worked for a university or research institute
   ☐ Other: ______________________________

3. Were you involved in or familiar with any of the DOE programs/activities related to alternative refrigerants? Check all that apply.

	Directly Involved	Very Familiar	Somewhat Familiar
▪ Mixed Refrigerants Research	☐	☐	☐
▪ Generic Research on New Refrigerants	☐	☐	☐
▪ AFEAS CRADA	☐	☐	☐
▪ MCLR Program	☐	☐	☐
▪ Other	☐	☐	☐

   Please give a brief description:

4. Have you ever received DOE funding for your work or participated in collaborative R&D activities with a DOE-funded laboratory such as Oak Ridge National Laboratory or the National Energy Technology Laboratory?
   ☐ No ☐ Yes. Please give a brief description:

5. In the past 15 years, have you been involved in commercial R&D related to refrigerants, air conditioning, or heat pumps?

   ☐ No (please skip down to Section III)
   ☐ Yes

SECTION II. This next set of questions pertains to DOE's involvement in and impact on the R&D activities that you were involved in. We will be asking you to quantify these impacts to the best of your ability.
Ask these questions if the respondent answered Yes to Question 5.
We are trying to isolate the impact of DOE R&D investments and activities as much as possible, and this poses some challenges. For example, efficiency standards and regulated phaseout of certain refrigerants affect companies' incentives to perform R&D and commercialize new products, and the DOE R&D activities we are focused on have indirect effects on the evolution of standards and regulations. Similarly, EnergyGuide labeling, ENERGY STAR qualification and rebates rely on test methods linked to DOE R&D activities.

Therefore, if we were to hold fixed the exact timeline of these factors (for instance, the timing of updates to standards) we would be assuming away a part of the impact we are trying to estimate. What we would like to try to do instead is to think about holding constant the environment—the institutional frameworks—in which standards, labeling, and subsidies evolve, and consider what would happen without the DOE R&D-related activities and investments described in Question 6:

6. In what ways has your R&D work been influenced by DOE?

   Provide a number from 0 to 3 (0 = DOE did not contribute in this way; 1 = minimal DOE contribution; 2 = moderate DOE contribution; 3 = major DOE contribution).

   _____Through DOE's contributions to the knowledge base on which R&D work drew (e.g., formal science literature, conference presentations and discussions, patents, knowledge and training of yourself and your colleagues)

   _____Through access to scientific and engineering data produced by DOE laboratories

   _____Through the licensing/transfer of technology that DOE helped to develop

   _____Through consultations with DOE scientists and engineers

   _____Through access to DOE laboratory facilities

   _____Through equipment/component testing performed at DOE laboratories

   _____Through direct R&D funding from DOE

   _____Other: _______________________________

   ☐ DOE had no influence (please skip down to question 8)

   Please give a brief description of DOE influences:

7. Would your R&D work have been undertaken without the DOE factors identified above? (please select the most likely scenario)

☐ The work would not have been undertaken

☐ At least some of the work would still have been undertaken, but the effort levels, costs, timelines, and/or outcomes would have been different

☐ The work would still have been undertaken, without significant difference in effort levels, costs, timelines, or outcomes (please skip down to question 9)

Please give a brief description of how effort levels, costs, timelines, and/or outcomes would have been different (or why the work would not have been undertaken). (Note: If the work would not have been undertaken at all, please skip down to question 8):

8. Without the DOE factors identified above:

☐ The level of effort, in terms of research personnel years, would have been

______________ research personnel years [☐ MORE ☐ LESS] (a range is fine).

OR _______________ % [☐ MORE ☐ LESS] (a range is fine).

☐ The cost of the work would have been

$______________ x1000 $ [☐ MORE ☐ LESS] (a range is fine).

OR _______________ % [☐ MORE ☐ LESS] (a range is fine).

☐ To reach the same outcomes (in terms of energy efficiency and other performance attributes) would have taken

_________________ calendar years [☐ MORE ☐ LESS] (a range is fine).

OR _______________ % [☐ MORE ☐ LESS] (a range is fine).

If any of the DOE factors identified in question 6 were especially important for one or more of these impacts, please give a short explanation:

9. What were the technical outcomes of your R&D work? Where possible, please provide the baseline parameter and improved parameter (e.g., pre and post energy efficiency, or pre and post equipment cost).

☐ Improvements in energy efficiency

Please describe:

☐ Improvements in other performance attributes

Please describe:

☐ Improvements in equipment cost for which these levels of energy efficiency or other performance attributes could be achieved

Please describe and include cost savings:

10. If DOE factors identified above had any impact on these outcomes, what was the DOE effect in terms of the proportion of the improvements you view were attributable to DOE activities?

Improvements in Energy Efficiency	**Improvements in performance attributes**	**Improvements in equipment costs**
☐ Less than 10%	☐ Less than 10%	☐ Less than 10%
☐ Between 10-24%	☐ Between 10-24%	☐ Between 10-24%
☐ Between 25-49%	☐ Between 25-49%	☐ Between 25-49%
☐ Between 50-75%	☐ Between 50-75%	☐ Between 50-75%
☐ Greater than 75%	☐ Greater than 75%	☐ Greater than 75%

Please give a short explanation of your reasoning. Please note if any of the DOE factors checked above were especially important for one or more of these impacts:

11. Was a new product commercialized as a result of this R&D work?
    - ☐ No (please skip down to Section III)
    - ☐ Yes

12. Without the DOE factors identified in question 6, taking into account the impacts on energy efficiency, other performance attributes, and equipment cost described above:

    c. How likely is it that your company would have commercialized the product in the same time frame (please select one)?

    ☐ No chance the product would have been commercialized.

    ☐ 0% to 25% chance

    ☐ 25% to 50% chance

    ☐ 50% to 75% chance

    ☐ 75% to 100% chance

    ☐ The product would have been commercialized in the same time frame without the DOE factors identified above.

    d. If your company had commercialized the product without the DOE factors identified above, how would its sales volume today compare with that of the product actually commercialized?

    ☐ No difference in sales (i.e., any difference in price, energy efficiency, and performance attributes would have negligible effect on sales)

☐ Sales would have been lower by roughly _________% (a range is fine).

☐ Sales would have been higher by roughly_________% (a range is fine).

Please give a short explanation of your reasoning:

(Respondents answering Section II questions skip to Section IV)

SECTION III. This next set of questions pertains to your opinion of DOE's influence on the market and industry trends for refrigeration systems in general.

We are trying to isolate the impact of DOE R&D investments and activities as much as possible, and this poses some challenges. For example, efficiency standards and regulated phaseout of certain refrigerants affect companies' incentives to perform R&D and commercialize new products, and the DOE R&D activities we are focused on have indirect effects on the evolution of standards and regulations. Similarly, EnergyGuide labeling, ENERGY STAR qualification and rebates rely on test methods linked to DOE R&D activities.

Therefore, if we were to hold fixed the exact timeline of these factors (for instance, the timing of updates to standards) we would be assuming away a part of the impact we are trying to estimate. What we would like to try to do instead is to think about holding constant the environment—the institutional frameworks—in which standards, labeling, and subsidies evolve, and consider what would happen without the DOE R&D-related activities and investments described in Question 13:

13. How did DOE impact the commercial R&D (performed in the last 15 years) necessary for companies to bring new refrigerants and more energy-efficient air conditioning and heat pump systems to market?

    Provide a number from 0 to 3 (0 = DOE did not contribute in this way; 1 = minimal DOE contribution; 2 = moderate DOE contribution; 3 = major DOE contribution).

    _____Through DOE's contributions to the knowledge base on which R&D work drew (e.g., formal science literature, conference presentations and discussions, patents, knowledge and training of yourself and your colleagues)

    _____Through access to scientific and engineering data produced by DOE laboratories

    _____Through the licensing/transfer of technology that DOE helped to develop

    _____Through consultations with DOE scientists and engineers

    _____Through access to DOE laboratory facilities

    _____Through equipment/component testing performed at DOE laboratories

    _____Through direct R&D funding from DOE

    _____Other: _________________________________

    _____DOE had no influence (please skip down to question 16)

    Please give a brief description of DOE influences:

14. Without the DOE impacts discussed in Question 13, would the commercial R&D necessary to bring new refrigerants and more energy-efficient air conditioning and heat pump systems to market still have been undertaken within the same time frame?

☐ The commercial R&D would not have been undertaken.

☐ At least some of the commercial R&D would still have been undertaken, but the effort levels, costs, timelines, and/or outcomes would have been different.

☐ The commercial R&D would still have been undertaken, without significant difference in effort levels, costs, timelines, or outcomes.

Please give a brief explanation:

15. Given your answers to Question 13, how would the market for refrigerants, air conditioning systems, and heat pumps look different than it does today without the DOE impacts discussed above?

☐ Average energy use would be: ☐ higher
☐ lower
by roughly _____________ %.

☐ Average price would be: ☐ higher
☐ lower
by roughly _____________ %.

☐ Average sales volume would be: ☐ higher
☐ lower
by roughly _____________ %.

☐ There would be no difference (the market would be exactly as it is today).

Please give a brief explanation:

Section IV. Additional Comments

16. Are there any additional comments you would like to share?

Respondent Contact Information (optional)
Name: ____
Title: ____
Division: ____
Company/Organization: ____
Location, if not USA: ____

Would you be willing to be contacted for a brief follow-up discussion of your responses to this survey?

☐ Yes, by phone _______________________
☐ Yes, by email _______________________
☐ No

THANK YOU for contributing your time and insight to the study.

Appendix B: Design of Knowledge Benefit Assessment

B-1 IDENTIFYING DOE PATENTS FOR THE STUDY

Using a multi-step process (described below), we identified a final list of 110 HVAC US patents funded by BTO; 49 Appliances US patents funded by DOE; and 25 Water Heating US patents funded by DOE. We then searched for equivalents of each of these patents in the EPO and WIPO systems. An equivalent is a patent filed in a different patent system covering essentially the same invention. We also searched for US patents that are continuations, continuations-in-part, or divisional applications of each of the patents in the final set. Having identified these equivalents, we then grouped the patents into families by matching priority documents (see earlier discussion of patent families).

A summary of the number of DOE funded patents and patent families in each of the three technologies is shown in Table 2.

Table 1 – Number of BTO-attributed Patents and Patent Families by Technology

	# Patent Families	# US Patents	# EPO Patents	# WIPO Patents
HVAC	106	115	19	28
Appliances	47	50	6	11
Water Heating	23	25	2	6

In HVAC, we identified a total of 115 US patents, 19 EPO patents, and 28 WIPO patents that are related to the initial 110 US patents (including these initial patents). These patents were grouped into 106 patent families.

In Appliances, we identified a total of 50 US patents, 6 EPO patents, and 11 WIPO patents that are related to the initial 49 US patents (including these initial patents). These patents were grouped into 47 patent families.

In Water Heating, we identified a total 25 US patents, 2 EPO patents, and 6 WIPO patents that are related to the initial 25 US patents (including these initial patents). These patents were grouped into 23 patent families.

The resulting list of patents used in the study is included at the end of this Appendix.

B1.1 The process for constructing the DOE-attributed HVAC, Appliances and Water Heating patents in brief was the following:

Identify DOE-Funded Patents - 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. In order 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.

Constructing a patent list for a government agency is more complicated, because the agency may fund research carried out at many different organizations. For example, DOE operates a number of laboratories and research centers, such as Ames, Argonne, Berkeley, Brookhaven, Livermore, Los Alamos, Oak Ridge and Sandia. Patents emerging from these laboratories and research centers may be assigned to DOE. However, the patents may also be assigned to the organization that manages a given laboratory or research center. 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. If this research results in patented inventions, these patents are likely to be assigned to the company carrying out the research, rather than to DOE.

For the purpose of studies such as this, 1790 Analytics has constructed a database of DOE funded patents. These include patents assigned to DOE itself, and also patents assigned to individual labs, lab managers and other organizations funded by DOE. The database is constructed using three primary sources:

1. ***OSTI Database*** – the first source is a database of DOE-funded patents put together by DOE's Office of Scientific & Technical Information (OSTI), and available on the web at www.osti.gov/doepatents/. This database contains information on research grants provided by DOE. It also links these grants to the organizations or DOE labs that carried out the research, the sponsor organization within DOE, and the US patents that resulted from these DOE grants.
2. ***Patents assigned to DOE*** – we identified a small number of US patents assigned to DOE that were not in the OSTI database. These patents were added to the list of DOE patents.
3. ***Patents with DOE Government Interest*** – a US 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. We identified all patents 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 typically denote DOE grants. Patents in this set that were not in the OSTI database, or assigned to DOE, were added to our list of DOE patents.

The DOE patent database constructed from these three sources contains a total of 26,014 US patents issued between January 1976 and June 2015 (when the patent sets for this analysis were collated).

Identify Relevant DOE-Funded Patents via Classifications - having defined the universe of DOE-funded patents, the next step was to determine which of these patents are relevant to HVAC, Appliances and Water Heating technologies.

We used a two-step process to locate relevant patents within the DOE patent database. First, we identified a set of International Patent Classifications (IPCs) and Cooperative

Patent Classifications (CPCs) related to the three technologies included in the analysis.

We then retrieved all patents in the DOE database that are contained at least one of these patent classifications. The result of this first step is a superset of patents that could potentially be relevant to the analysis. The superset contained a total of 970 patents. Clearly, not all patents in this superset are relevant. For example, A47J contains patents related to kitchen equipment, and we are only interested in the subset of these patents related to appliances. Similarly, F25 contains patents related to refrigeration and cooling, and we are only interested in the subset of these patents related to refrigerators, air conditioners etc, and not patents related to cooling turbines, reactors etc.

One option to narrow the superset would have been to use keywords in addition to the patent classifications (which is the traditional approach to building a patent filter). However, given the manageable size of the superset, it was possible to use a more detailed, manual approach. Specifically, we read the titles and abstracts of all patents within the superset, in order to determine which of them appeared relevant to each of the three technologies.

Identify Relevant DOE Funded Patents based on BTO List - in addition to identifying patents via classifications, we were also provided with a set of relevant patents put together by staff at DOE's Building Technologies Office (BTO). We combined this set with the patent list generated via classifications. This resulted in a draft list of DOE funded patents in HVAC, Appliances and Water Heating technologies.

Review of Draft Patent List by DOE - we provided the draft patent list to DOE for review. We received feedback from DOE scientists and program managers as to which of the candidate patents should be included in our final set of DOE funded HVAC, Appliances and Water Heating patents, and which should be omitted.

***B*-2. Identifying HVAC, Appliances and Water Heating Patents Assigned to Leading Organizations**

The purpose of the backward tracing element of our analysis is to evaluate the impact of DOE funded research upon HVAC, Appliances and Water Heating technologies produced by leading companies in each of these industries. To identify such companies, we first defined the universe of patents in these three technologies using patent filters. We then located the ten most prolific patenting companies in each technology[40].

These patent filters were much more detailed than the one used to identify relevant DOE patents. The detailed filters were used due to practical considerations. In defining the DOE patent sets, candidate patents were read individually, first by 1790 and then by DOE, in order to determine their relevance. This process was possible because the number of patents involved was relatively small. The same process of reading individual patents is not practical when the patent set is drawn from the entire universe of patents, not just those patents funded by DOE.

The patent filters used to define the universes of HVAC, Appliances and Water Heating patents thus had to avoid introducing large numbers of irrelevant patents, since these patents could not be removed by reading them individually. These filters thus went beyond broad patent classifications, and instead used combinations of more specific classifications and keywords, as outlined below.

Identifying Top 10 Patenting HVAC Companies - the filter used to define the universe of HVAC patents is shown in Table 3.

Table 3 – Filter used to Identify HVAC Patents

Filter = (Search 1 OR Search 2 OR Search 3) ANDNOT (Search 4)
Search 1
IPC = F24F (Air Conditioning/Ventilation) or F24D 1-15 (Space Heating and Central Heating Systems) or F24H 3 (Air Heaters)
Search 2
IPC = (F25 (Refrigeration/Cooling) or F28 (Heat Exchange)) AND Title/Abstract = (air(?)condition* or ventilat* or HVAC)
Search 3

[40] These companies are sometimes referred to hereafter as the leading HVAC/Appliances/Water Heating companies. This is based on patent portfolio size, and is not a reflection number of units sold or revenues, profits etc. A fuller description would be the leading patenting HVAC/Appliances/Water Heating companies, but this is a cumbersome description to use throughout the results section of the report.

IPC = F24 (Heating/Ventilating) AND IPC = F25 (Refrigeration/Cooling)
Search 4
IPC = B60H (Heating/Cooling for Vehicles) OR Title/Abstract = (car or cars or vehicle* or automobile*)

This filter consists of a total of four separate searches. Search 1 contains a series of specific IPCs that are related directly to HVAC technologies. Search 2 uses broader IPCs in combination with keywords, in order to locate patents relevant patents that are outside the specific IPCs in Search 1. Search 3 identifies patents that are classified in both refrigeration and heating/ventilation. These patents are mainly concerned with air conditioning, particularly the use of coolant materials. Patents identified by any of the three searches are included in the initial HVAC set.

Search 4 differs from the other three searches in the filter, in that it is used to remove patents from this initial HVAC set, specifically patents directed to heating and air conditioning systems for vehicles. There are large numbers of such patents, and their inclusion would skew the analysis towards automobile companies, rather than domestic HVAC companies. The final patent set thus contains patents identified by any of the three initial searches, minus patents identified by the final vehicle-related search.

Using this HVAC filter, we identified a total of 10,006 US patents, 12,484 EP patents and 11,447 WO patents, a total of 33,937 patent documents overall. We grouped these documents into 28,828 patent families based on matching priority documents.

The ten companies with the largest number of HVAC patent families are shown in Table 4. This includes patent families associated with all variant names under which the companies have patents, including all subsidiary names. The HVAC patent families of these ten companies form the starting point of the backward tracing in this technology.

Table 4 – Top 10 Patenting HVAC Companies

Company	# HVAC Patent Families
Daikin Industries	1278
Mitsubishi Electric	1265
LG Electronics	957
Panasonic	883
United Technologies	798
Samsung Electronics	346

Toshiba	308
Sharp	265
Hitachi	260
Honeywell International	239

The largest HVAC patent portfolios are owned by Daikin Industries (1,278 patent families) and Mitsubishi Electric (1,265 families). There is then a gap to the next three companies: LG Electronics (957 patent families); Panasonic (883 families); and United Technologies (798 families). In turn, there is a further gap to the five companies that round out the top ten list: Samsung (346 families); Toshiba (308); Sharp (265); Hitachi (260) and Honeywell (239).

Identifying Top 10 Patenting Appliances Companies - of the filters used to define the universe of patents in each of the three technologies, the one directed to Appliances patents is the most complicated. Patents for different types of Appliances are allocated to different patent classifications, rather than being contained in a single Appliances classification. As a result, we designed separate searches for the various types of Appliances, as shown in Table 5. These searches cover the following types of Appliances: refrigerators, dishwashers, washing machines, clothes dryers, stoves, and microwaves. We did not extend the searches to cover smaller appliances (such as coffee makers, toasters, blenders etc), since there are many such appliances, each of which would require a separate search, thus making the final filter very complicated and time-consuming to construct.

Table 5 – Filter used to Identify Appliances Patents

Filter = (Search 1 OR Search 2 OR Search 3 OR Search 4 OR Search 5 OR Search 6)
Search 1 (Refrigerators)
IPC = F25D 11 (Domestic Refrigerators) OR (IPC = F25D (Refrigerators) and Title/Abstract = (domestic* or house(?)hold*))
Search 2 (Dishwashers)
IPC = A47L 15 (Washing Machines for Crockery or Tableware) OR (IPC = B08B 3 (Cleaning using Liquid/Steam) and Title/Abstract = (dish(?)wash* or wash*(?)dish*))
Search 3 (Washing Machines)
(IPC = D06F 9-39 (Washing Machines for Textile Articles) andnot (IPC = A47L 15 (Washing Machines for Crockery or Tableware))
Search 4 (Dryers)

(IPC = D06F 49 (Domestic Spin Dryers) or D06F 58 (Domestic Laundry Dryers)) ANDNOT IPC = A47L 15 (Washing Machines for Crockery or Tableware)
Search 5 (Stoves)
IPC = F24C 5, 7, 13-15 (Stoves/Ranges) AND Title/Abstract = (hob* or oven* or range* or stove* or cook(?)top*
Search 6 (Microwaves)
IPC = F24C 7/02 (Stoves using Microwaves) OR (IPC = H05B 6/64-80 (Heating using Microwaves) and Title/Abstract = (food* or oven* or cook*)) OR (IPC = F24C (Stoves/Ranges) and Title/Abstract = micro(?)wave*)

Using this Appliances filter, we identified a total of 7,900 US patents, 14,625 EP patents and 9,107 WO patents, a total of 31,632 documents overall. We grouped these documents into 25,346 patent families based on matching priority documents.

The ten companies with the largest number of Appliances patent families (including all variant and subsidiary names) are shown in Table 6. The Appliances patent families of these ten companies form the starting point of the backward tracing in this technology.

BSH Hausgeräte[41] has the largest Appliances patent portfolio with 2,893 families, followed by LG Electronics with 1,980 families, AB Electrolux (1,955 families) and Whirlpool (1,798 families). There is then a gap to Samsung (1,054 families), Koc Holding (821 families) and Panasonic (766 families) and the list is completed by Miele & Cie, General Electric and Sharp, with 553, 466 and 290 families respectively.

Table 6 – Top 10 Patenting Appliances Companies

Company	# Appliances Patent Families
BSH Hausgeräte	2893
LG Electronics	1980
AB Electrolux	1955
Whirlpool	1798
Samsung Electronics	1054
Koc Holding	821
Panasonic	766
Miele & Cie	553

[41] BSH Hausgeräte was set up in 1967 as a joint venture between Bosch and Siemens. In 2015, Bosch purchased Siemens' share of BSH, making a wholly-owned subsidiary of Bosch. However, for almost all of the period studied in this analysis, BSH was still a joint venture, and so is kept separate from the Bosch parent company in the analysis.

General Electric	466
Sharp	290

Identifying Top 10 Patenting Water Heating Companies - the filter used to identify Water Heating patents is shown in Table 7. This filter consists of three separate searches. Search 1 contains a series of IPCs directed specifically to water heaters, while Search 2 contains broader IPCs in combination with keywords. Patents identified by either search are included in the initial Water Heating set. Search 3 is then used to eliminate patents from this initial set, specifically patents describing vehicle applications, and patents describing water heating in small appliances, such as coffee makers and tea kettles.

Table 7 – Filter used to Identify Water Heating Patents

Filter = (Search 1 OR Search 2) ANDNOT Search 3
Search 1
IPC = F24D 17 (Domestic Hot Water Supply Systems) or IPC = F24H 1, 4, 6, 7, 9 (Water Heaters with Heat Generating Means)
Search 2
IPC = (F24 (Heating/Ventilating) or F25 (Refrigeration/Cooling) or F28 (Heat Exchange)) AND Title/Abstract = ((boiler or water(?)heat*) AND (domestic or house(?)hold or central(?)heat*))
Search 3
Search 3 IPC = A47 (Domestic Appliances) OR IPC = B60H (Heating/Cooling for Vehicles) OR Title/Abstract = (kettle* or coffee or beverage* or food* or car or cars or vehicle* or automobile or air(?)condition*)

Using this Water Heating filter, we identified a total of 2,191 US patents, 3,694 EP patents and 2,557 WO patents, a total of 8,442 patent documents overall. We grouped these documents into 7,328 patent families based on matching priority documents.

The ten companies with the largest number of Water Heating patent families (including all variant and subsidiary names) are shown in Table 8. The Water Heating patent families of these ten companies form the starting point of the backward tracing in this technology.

Table 8 – Top 10 Patenting Water Heating Companies

Company	# Water Heating Patent Families
Bosch	188
Vaillant	154
A.O. Smith	139
Panasonic	127
Viessmann	126
Paloma Industries	87
Daikin Industries	73
Mitsubishi Electric	61
Kyung Dong Navien	60
BSH Hausgeräte	59

There are five companies with more than 100 Water Heating patent families: Bosch (188 families); Vaillant (154); A.O. Smith (139); Panasonic (127); and Viessmann (126). The remaining five companies each have between 50 and 100 patent families – Paloma (87 families); Daikin (73); Mitsubishi Electric (61); Kyung Dong Navien (60) and BSH Hausgeräte (59).

B-3. CONSTRUCTING CITATION LINKS

Through the processes described above, we constructed starting patent sets for both the forward tracing and backward tracing elements of the analysis. The patent set for the forward tracing consisted of DOE-funded patent families in HVAC, Appliances and Water Heating. The patent set for the backward tracing consisted of patent families assigned to the top ten patenting companies in each of these three technologies.

Having defined these patent sets, we then traced forward through two generations of citations from the DOE patents, and backward through two generations of citations from the leading company patents. These included citations listed on US, EPO and WIPO patents, and required extensive data cleaning to account for differences in referencing formats across these systems. The citation linkages identified, along with characteristics of the starting patent sets, form the basis for the results presented in the body of the report.