The Influence of HVAC, Water Heating, and Appliance Patents Funded by the U.S. Department of Energy's Building Technologies Office and other DOE Offices

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Executive Summary

This report describes the results of an analysis tracing the technological influence of building technologies research funded by the Building Technologies Office (BTO) in the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) and its precursor programs – as well as building technologies research funded by other offices in DOE. The report covers three distinct technologies: heating, ventilation and air conditioning (HVAC); appliances; and water heating. These are considered to be separate technologies. Each is analyzed individually, and the report contains separate results sections for the three technologies.

The influence tracing in this report is carried out both backwards and forwards in time, and focuses on patents filed in three systems: the U.S. Patent & Trademark Office (U.S. patents); the European Patent Office (EPO patents); and the World Intellectual Property Organization (WIPO patents). The primary period covered in this analysis is 1976 to 2018.

The main purpose of the backward tracing is to determine the extent to which BTO-funded building technologies research has formed a foundation for innovations patented by leading building technologies companies. Meanwhile, the primary purpose of the forward tracing is to examine the broader influence of BTO-funded building technologies research upon subsequent technological developments, both within and outside building technologies technology. In addition to these BTO-based analyses, we also extend many elements of the analysis to other DOE-funded building technologies patents, in order to gain insights into their influence.

Heating, Ventilation and Air Conditioning (HVAC)

The main finding from the HVAC element of this report is:

- DOE-funded patenting in HVAC technology has been relatively consistent over time, with BTO-funded patents representing a high percentage of the total. Given their comparatively small size, the portfolios of BTO-funded and Other DOE-funded HVAC patents have had a notable influence on subsequent innovations associated with the leading companies in HVAC technology. The influence of these patents also extends beyond HVAC into other technologies, including advanced materials, solar thermal energy and semiconductor manufacturing.

More detailed findings from the HVAC element of this report include:

- In HVAC technology, in the period 1976-2018, we identified a total of 69,099 patents (24,514 U.S. patents, 21,817 EPO patents and 22,768 WIPO patents). We grouped these patents into 51,821 patent families, with each family containing all patents resulting from the same initial application (named the priority application).

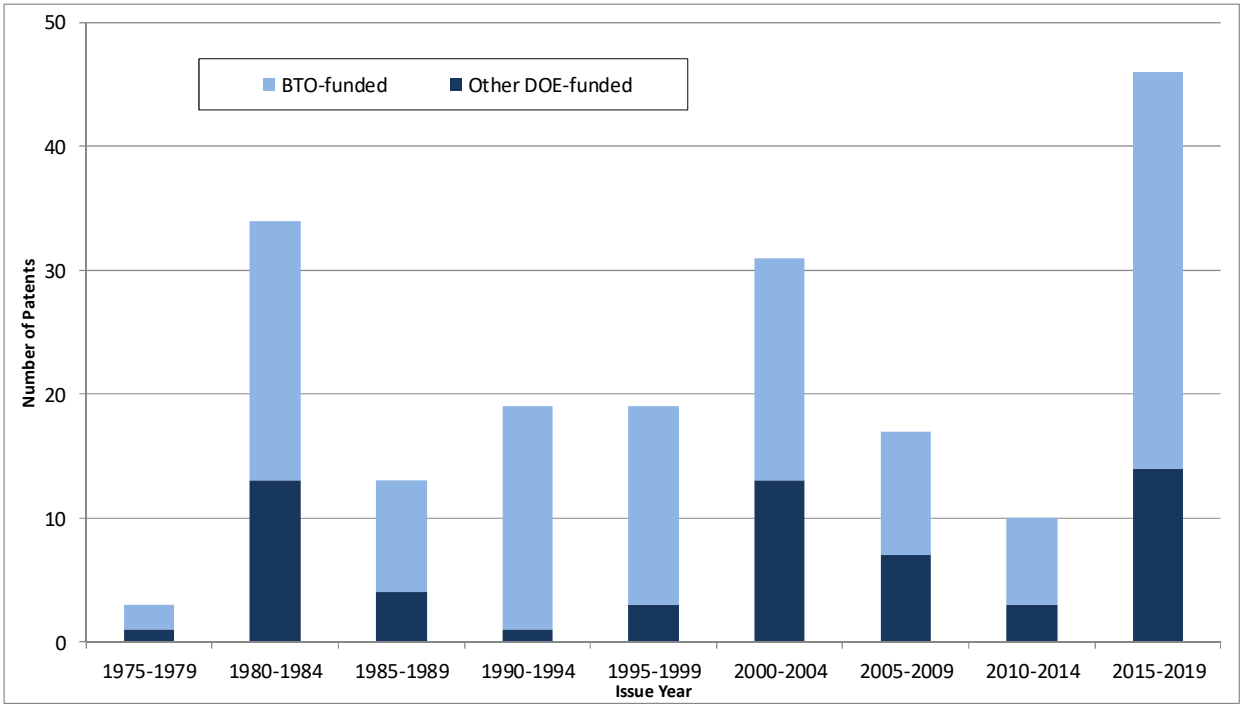
- 190 HVAC patents are confirmed to be associated with BTO funding (134 U.S. patents, 23 EPO patents, and 33 WIPO patents). We grouped these BTO-funded HVAC patents into 113 patent families.

- In addition, we identified a further 81 HVAC patents (59 U.S. patents, 9 EPO patents and 13 WIPO patents) that are associated with DOE funding. These "Other DOE-funded" patents are grouped into 51 patent families.

- The total number of DOE-funded HVAC patents (BTO-funded plus Other DOE-funded) is 271, corresponding to 164 patent families. This represents 0.32% of the total number of HVAC patent families in the period 1976-2018.

- Figure HV-E1 shows the number of HVAC granted U.S. patents funded by DOE. There is no consistent overall trend in this figure, with time periods of active patenting interspersed with periods with many fewer patents. The peaks in the number of U.S. patents occurred in 1980-1984 (34 patents), 2000-2004 (31 patents) and 2015-2019 (46 patents). In each of the time periods, there were more BTO-funded patents than Other DOE-funded patents, with the former also representing the bulk of the patents throughout the 1990s.

Figure HV-E1 - Number of HVAC Granted U.S. Patents Funded by BTO and Other DOE Sources by Issue Year (5-Year Totals)



Note: The data collection period for this analysis ended with 2018. Any 2019 patents in the 2015-2019 column are additional patents that have been included because they are members of the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

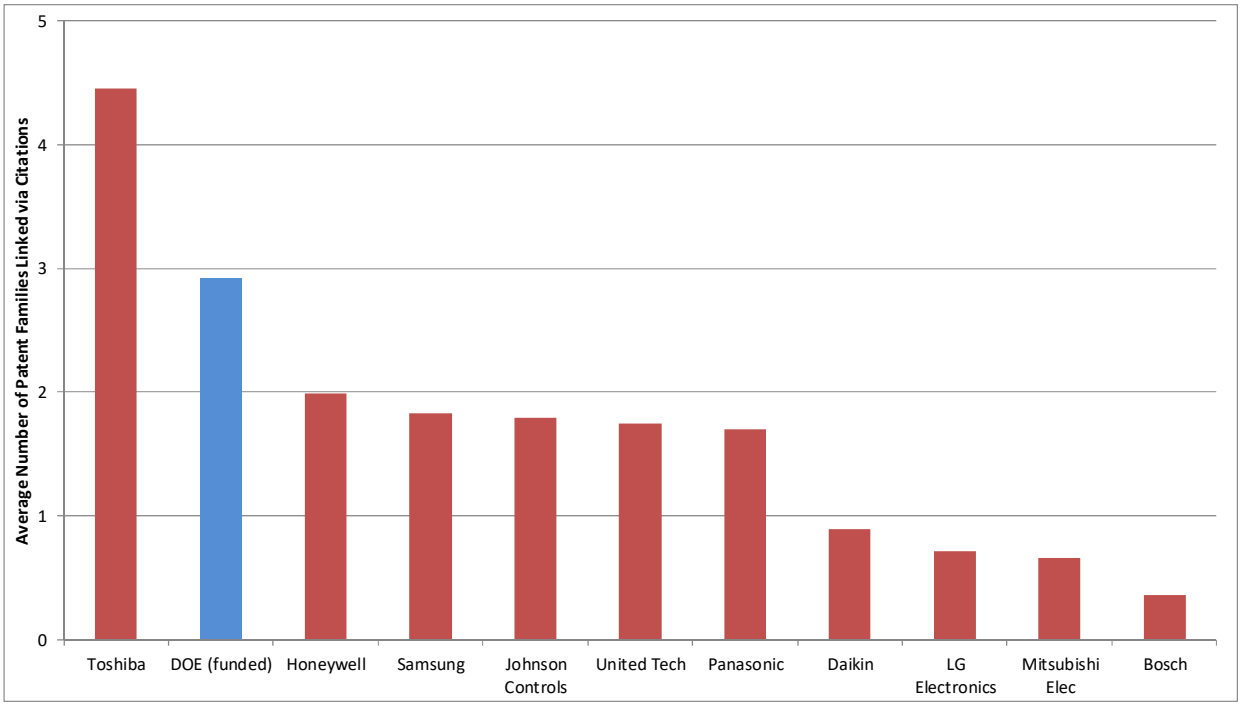
- The ten companies with the largest number of HVAC patent families are: Mitsubishi Electric (3,367 families); Daikin Industries (1,744); United Technologies (1,411); LG Electronics (1,361); Panasonic (1,297); Honeywell (647); Samsung (611); Bosch (604); Johnson Controls (475); and Toshiba (468). Six of these companies are based in Asia, two in Europe and two in North America. The portfolios of DOE-funded HVAC patent

families (113 BTO-funded; 51 Other DOE-funded) are much smaller than those of the leading companies, which is taken into account when assessing their relative influence.

- BTO-funded HVAC patents have a particular focus on absorption heating and cooling, heat exchanger components and desiccants for air conditioning systems. Meanwhile, the patents assigned to the leading companies have a greater emphasis on air conditioning control systems and compressors. This difference in focus suggests that, in the period 1976-2018, BTO funding helped fill a research gap not addressed extensively by the leading companies.

- Figure HV-E2 shows that, on average, DOE-funded HVAC patent families (the majority of which are BTO-funded) are each linked to just under three patent families assigned to the leading companies. This puts DOE-funded patents in second place in this figure, behind Toshiba. It means that, on average, more HVAC patent families owned by leading companies are linked via citations to each DOE-funded HVAC patent family than are linked to the HVAC patent families assigned to any other leading company (except Toshiba). Figure HV-E2 thus suggests that, taking into account its relatively small size, the portfolio of DOE-funded HVAC patents has had a notable influence on HVAC innovations associated with the leading companies.

Figure HV-E2 – Average Number of Leading Company HVAC Patent Families Linked via Citations to HVAC Families from Each Leading Company
e.g. on average, each DOE-funded patent family is linked to just under three subsequent patent families assigned to leading companies



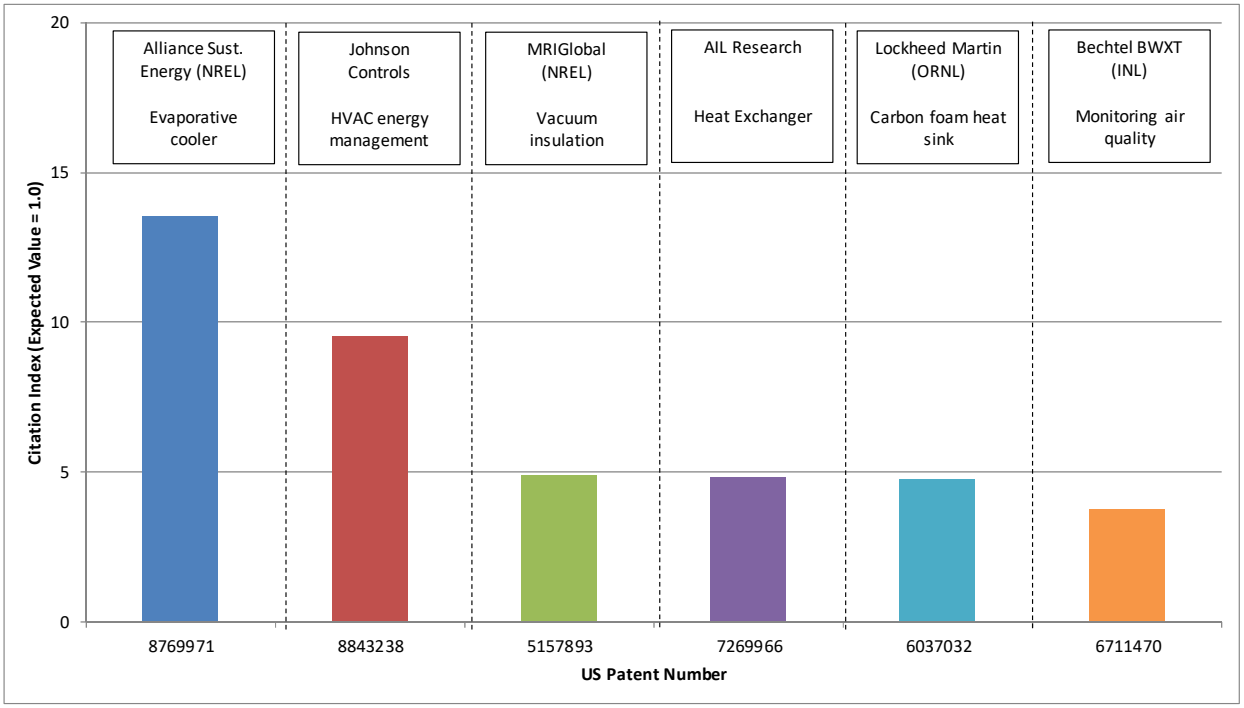
- Four of the ten leading HVAC companies have more than 5% of their patent families linked via citations to DOE-funded patents. These companies are headed by Honeywell, with 13.5% of its HVAC patent families linked via citations to earlier DOE-funded

HVAC patents (11.6% linked to BTO-funded HVAC patents). Johnson Controls has 9.1% of its families linked via citations to DOE (7.8% to BTO), followed by United Technologies (7.4% linked to DOE; 5.5% to BTO) and LG Electronics (5.4% linked to DOE; 4.2% to BTO).

- BTO-funded HVAC patents have an average Citation Index of 1.43 (the Citation Index is a normalized citation metric with an expected value of 1.0; a value of 1.43 shows that, based on their age and technology, BTO-funded HVAC patents have been cited as prior art 43% more frequently than expected by subsequent patents). This puts BTO-funded HVAC patents in third place among the leading companies, behind only Honeywell and Johnson Controls. The Citation Index for Other DOE-funded HVAC patents is lower at 0.99, but this still means these patents have been cited around as frequently as expected.

- There are a number of individual high-impact BTO-funded HVAC patents, examples of which are shown in Figure HV-E3. They include patents from the National Renewable Energy Laboratory describing evaporative coolers (US #8,769,971) and vacuum insulation (US #5,157,893). Since being granted in 2014, the former has been cited as prior art by 37 subsequent patents, thirteen times as many citations as expected given its age and technology. Meanwhile, the latter has been cited by 108 subsequent patents since it was granted in 1992, almost five times as many citations as expected. This figure also includes highly-cited patents from Johnson Controls for HVAC energy management, AIL Research for heat exchangers, Lockheed Martin (Oak Ridge National Laboratory) for carbon foam heat sinks, and Bechtel BWXT (Idaho National Laboratory) for an air quality monitoring system.

Figure HV-E3 – Examples of Highly-Cited BTO-funded HVAC Patents



Appliances

The main finding from the appliances element of this report is:

- DOE-funded appliance patenting was relatively consistent throughout the analysis period, with BTO-funded patents making up a high percentage of the total. BTO-funded patents focus primarily on refrigeration technology, while the patents of leading appliance companies have a much broader range, with a particular concentration on washers and dryers. That said, it is still possible to trace the influence of BTO-funded appliance research on the leading companies, especially in refrigeration and heat exchange technologies. Meanwhile, the influence of BTO-funded and Other DOE-funded appliance research can be seen on subsequent innovations beyond appliances, notably in nanocomposites, advanced materials and energy storage.

More detailed findings from the appliances element of this report include:

- In appliance technology, in the period 1976-2018, we identified a total of 51,734 patents (16,866 U.S. patents, 19,918 EPO patents and 14,950 WIPO patents). We grouped these patents into 35,876 patent families, with each family containing all patents resulting from the same initial application (named the priority application).

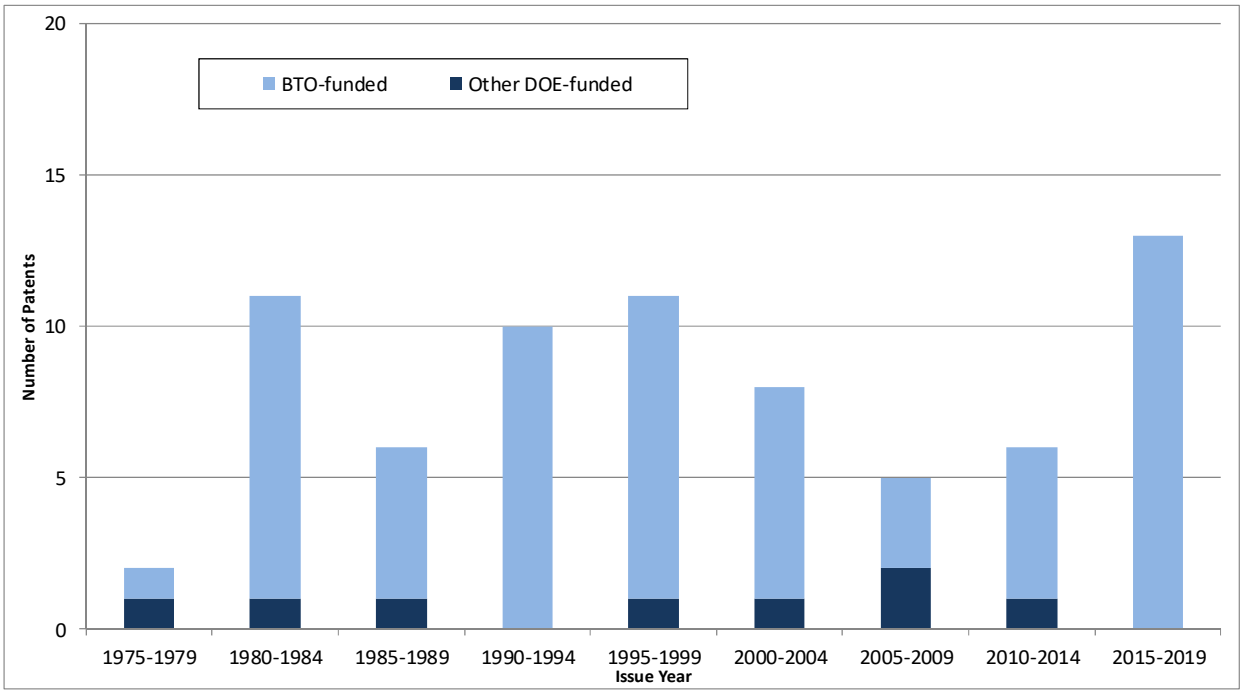
- 89 appliance patents are confirmed to be associated with BTO funding (64 U.S. patents, 14 EPO patents, and 11 WIPO patents). We grouped these BTO-funded appliance patents into 58 patent families.

- In addition, we identified a further eight appliance patents (all eight are U.S. patents) that are associated with DOE funding. These "Other DOE-funded" patents are grouped into eight patent families.

- The total number of DOE-funded appliance patents (BTO-funded plus Other DOE-funded) is 97, corresponding to 66 patent families. This represents 0.18% of the total number of appliance patent families in the period 1976-2018.

- Figure AP-E1 shows the number of appliance granted U.S. patents funded by DOE. This figure reveals that there is no consistent trend over time in the number of DOE-funded appliance patents. There are four periods where the number of patents reached double figures (11 in 1980-1984; 10 in 1990-1994; 11 in 1995-1999 and 13 in 2015-2019), interspersed with periods with lower numbers of patents. BTO-funded patents represent a high percentage of the total number of DOE-funded patents in each time period.

Figure AP-E1 - Number of Appliance Granted U.S. Patents Funded by BTO and Other DOE Sources by Issue Year (5-Year Totals)



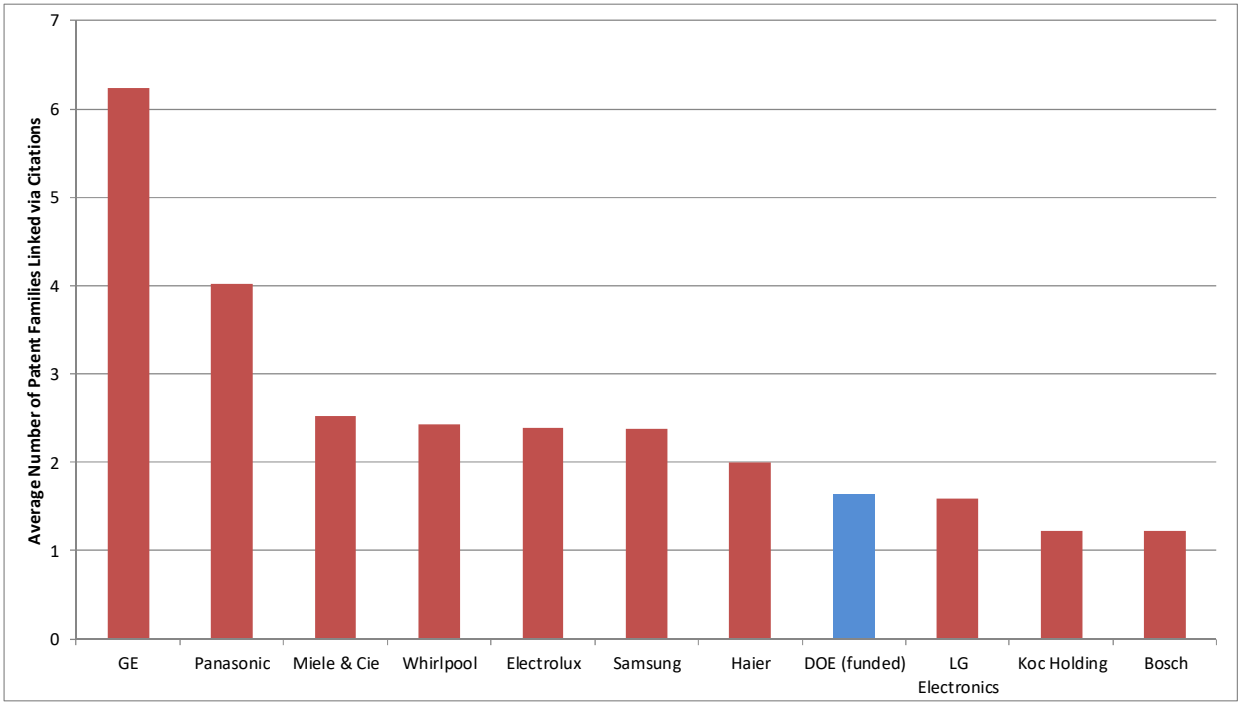
Note: The data collection period for this analysis ended with 2018. Any 2019 patents in the 2015-2019 column are additional patents that have been included because they are members of the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

- The ten companies with the largest number of appliance patent families are: Bosch (4,117 families); Whirlpool (3,071); LG Electronics (2,753); Electrolux (2,740); Samsung (1,424); Haier (1,384); Koc Holding (1,351); Panasonic (1,021); General Electric (840); and Miele & Cie (788). Four of these companies are based in Asia, four in Europe, and two in North America. The portfolios of DOE-funded appliance patent families (58 BTO-funded; 8 Other DOE-funded) are much smaller than those of the leading companies, which is taken into account when assessing their relative influence.

- BTO-funded appliance patents have a particular focus on refrigeration and cooling (specifically absorption and magnetic refrigeration, plus refrigeration compressors). The appliance patents assigned to the leading companies cover a broader range of technologies, with a particular concentration on washing machines and clothes dryers.

- Figure AP-E2 shows that, on average, DOE-funded appliance patent families (the majority of which are BTO-funded) are each linked to 1.6 patent families assigned to the leading companies. This puts DOE-funded patents in eighth place in this figure. Their relatively low position is not unexpected, given that their technological focus is very different to those of the leading companies. It is also reflected in a separate finding that only two of the leading companies – Haier and Whirlpool – have more than 1% of their appliance patent families linked via citations to earlier DOE-funded appliance patents.

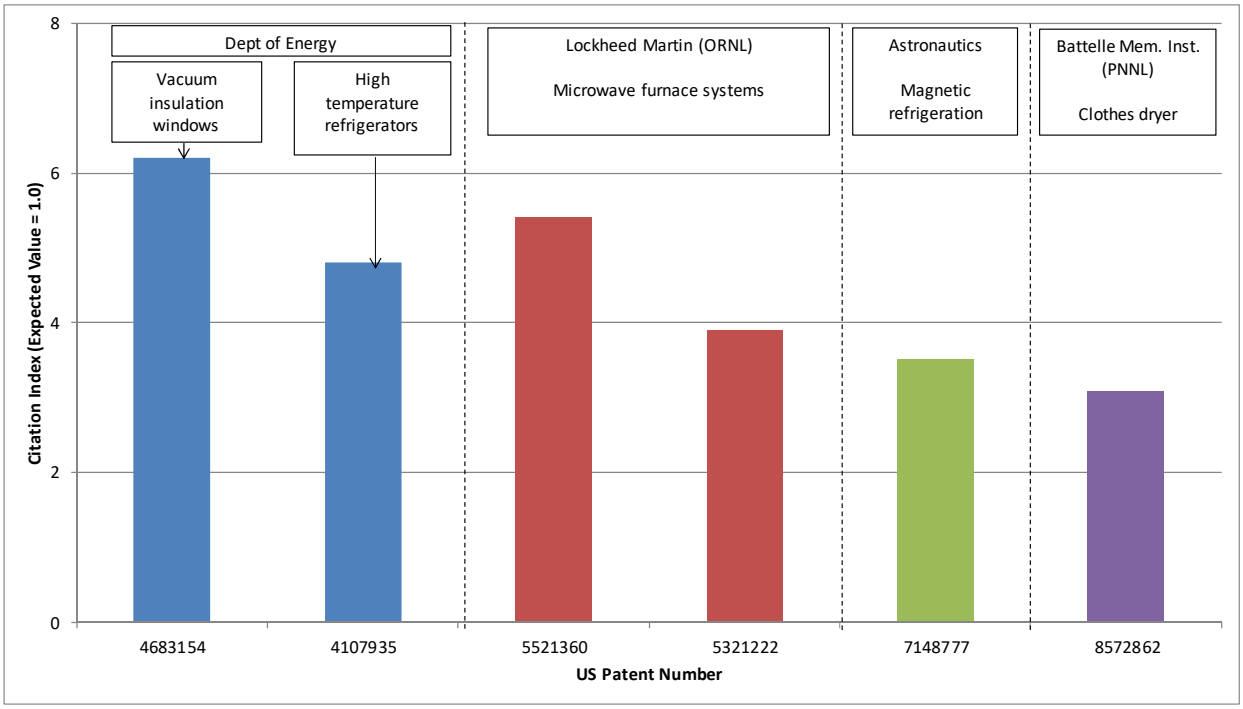
Figure AP-E2 – Average Number of Leading Company Appliance Patent Families Linked via Citations to Appliance Families from Each Leading Company
e.g. on average, each DOE-funded patent family is linked to 1.6 subsequent patent families assigned to leading companies



- BTO-funded appliance patents have an average Citation Index of 1.56 (the Citation Index is a normalized citation metric with an expected value of 1.0; a value of 1.56 shows that, based on their age and technology, BTO-funded appliance patents have been cited as prior art 56% more frequently than expected by subsequent patents). This is a higher average Citation Index than for each of the leading appliance companies. When evaluated alongside the finding reported in Figure AP-E2, this suggests that BTO-funded appliance patents have been relatively influential, but much of this influence has been on innovations not associated with the leading appliance companies.

- There are a number of individual high-impact BTO-funded appliance patents, examples of which are shown in Figure AP-E3. They include early patents assigned to DOE for vacuum insulation windows (US #4,683,154) and high temperature refrigerators (US #4,107,935). The former has been cited as prior art by 141 subsequent patents (over six times as many citations as expected given its age and technology), while the latter has been cited by 82 subsequent patents (almost five times as many as expected). They also include patents for microwave furnaces assigned to Lockheed Martin, through its management of Oak Ridge National Laboratory. One of these patents (US #5,521,360) has been cited by 105 subsequent patents, more than five times as many citations as expected. More recent highly-cited patents include a 2006 Astronautics patent (US #7,148,777) describing magnetic refrigeration, and a 2013 Pacific Northwest National Laboratory patent (US #8,572,862) for a clothes dryer.

Figure AP-E3 – Examples of Highly-Cited BTO-funded Appliance Patents



Water Heating

The main finding from the water heating element of this report is:

- DOE-funded patenting in water heating technology was relatively sparse throughout the time period analyzed. That said, given their relatively small size, the portfolios of DOE-funded (and especially BTO-funded) water heating patents have had a notable influence on subsequent innovations associated with leading companies in this technology. This influence can be seen both over time and across these leading companies, with their innovations related to heat pump water heaters and refrigeration cycles linked via citations to earlier BTO-funded water heating patents. The influence of BTO-funded and Other DOE-funded water heating research can also be seen across a range of other technologies, including electronics and semiconductor manufacturing, gas turbines and solar energy.

More detailed findings from the water heating element of this report include:

- In water heating technology, in the period 1976-2018, we identified a total of 10,933 patents (3,731 U.S. patents, 3,929 EPO patents and 3,273 WIPO patents). We grouped these patents into 8,340 patent families, with each family containing all patents resulting from the same initial application (named the priority application).

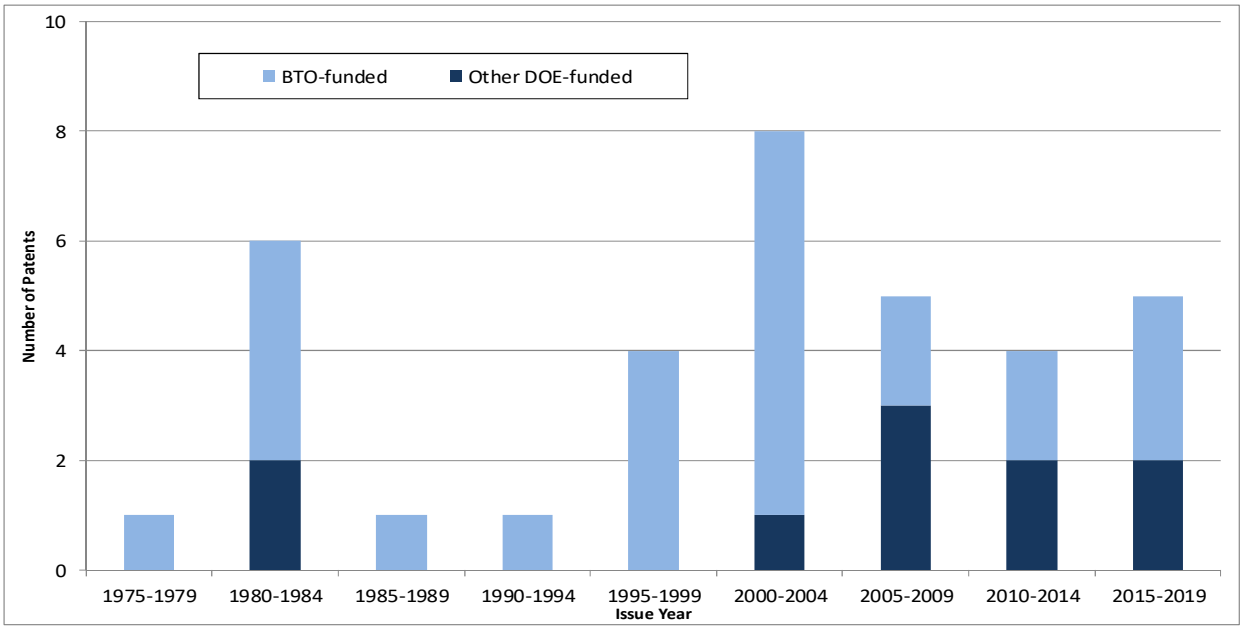
- 35 water heating patents are confirmed to be associated with BTO funding (25 U.S. patents, 2 EPO patents, and 8 WIPO patents). We grouped these BTO-funded water heating patents into 23 patent families.

- In addition, we identified a further 14 water heating patents (10 U.S. patents, 4 WIPO patents) that are associated with DOE funding. These "Other DOE-funded" patents are grouped into 10 patent families.

- The total number of DOE-funded water heating patents (BTO-funded plus Other DOE-funded) is 49, corresponding to 33 patent families. This represents 0.4% of the total number of water heating patent families in the period 1976-2018.

- Figure WH-E1 shows the number of water heating granted U.S. patents funded by DOE. This figure shows that patenting was relatively sparse in each time period. The peak was in 2000-2004, with eight DOE-funded U.S. patents granted, seven of which were funded by BTO. Overall, there are 35 DOE-funded U.S. patents, 25 of which are BTO-funded.

Figure WH-E1 - Number of Water Heating Granted U.S. Patents Funded by BTO and Other DOE Sources by Issue Year (5-Year Totals)



Note: The data collection period for this analysis ended with 2018. Any 2019 patents in the 2015-2019 column are additional patents that have been included because they are members of the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

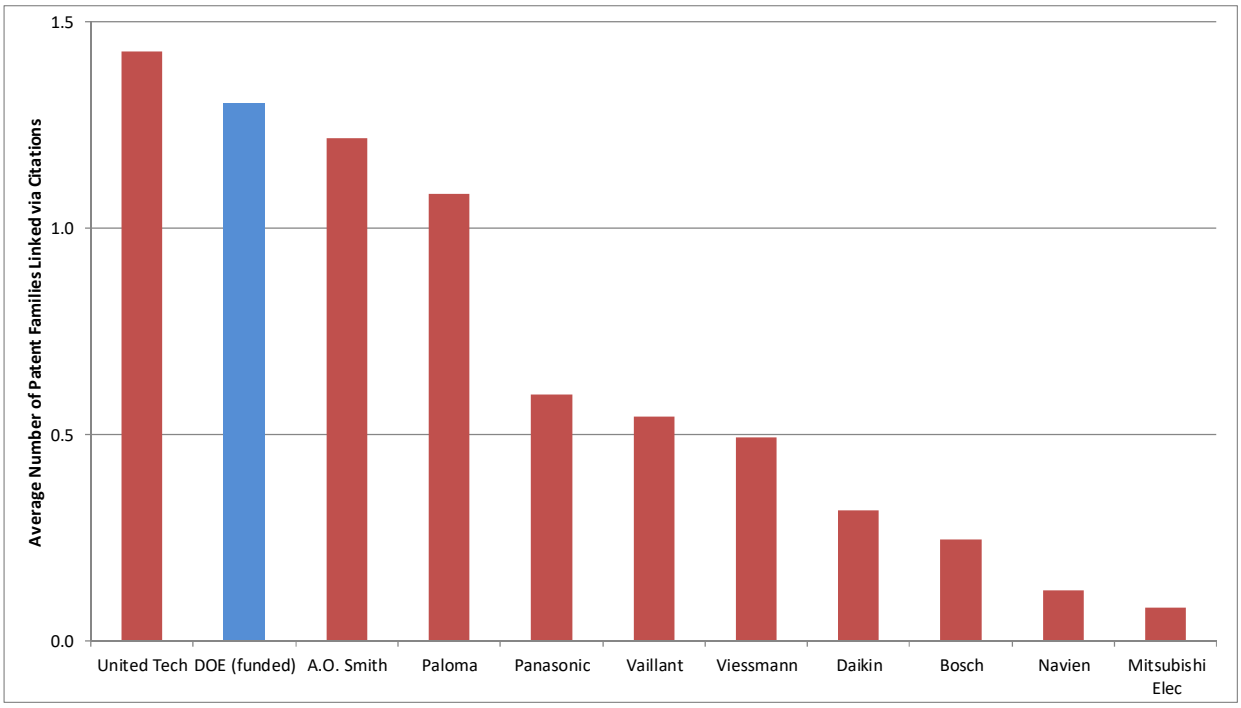
- The ten companies with the largest number of water heating patent families are: Bosch (286); A.O. Smith (229); Mitsubishi Electric (216); Vaillant (166); Paloma Industries (145); Kyung Dong Navien (107); Panasonic (97); Daikin Industries (79); United Technologies (77); and Viessmann (69). Four of these companies are based in Asia, four in Europe and two in North America. The portfolios of DOE-funded water heating patent families (23 BTO-funded; 10 Other DOE-funded) are smaller than those of the leading companies, which is taken into account when assessing their relative influence.

- BTO-funded water heating patents focus primarily on water cooled condensers, thermal energy storage and absorption-based technologies. The leading companies also have a notable presence in the first two of these technologies, but not in absorption-based

heating (a research gap that, in the period 1976-2018, BTO funding may thus have helped address). The leading companies also concentrate on water heating furnace tubes and water heaters with fluid combustibles.

- Figure WH-E2 shows that, on average, DOE-funded water heating patent families (the majority of which are BTO-funded) are each linked to 1.3 patent families assigned to the leading companies. This puts DOE-funded patents in second place in this figure, behind only United Technologies. It means that, on average, more water heating patent families owned by leading companies are linked via citations to each DOE-funded water heating patent family than are linked to the water heating patent families assigned to any other leading company (except United Technologies). This suggests that, taking into account its relatively small size, the portfolio of DOE-funded water heating patents has had a notable influence on water heating innovations associated with the leading companies.

Figure WH-E2 – Average Number of Leading Company Water Heating Patent Families Linked via Citations to Water Heating Families from Each Leading Company
e.g. on average, each DOE-funded family is linked to 1.3 subsequent leading company families



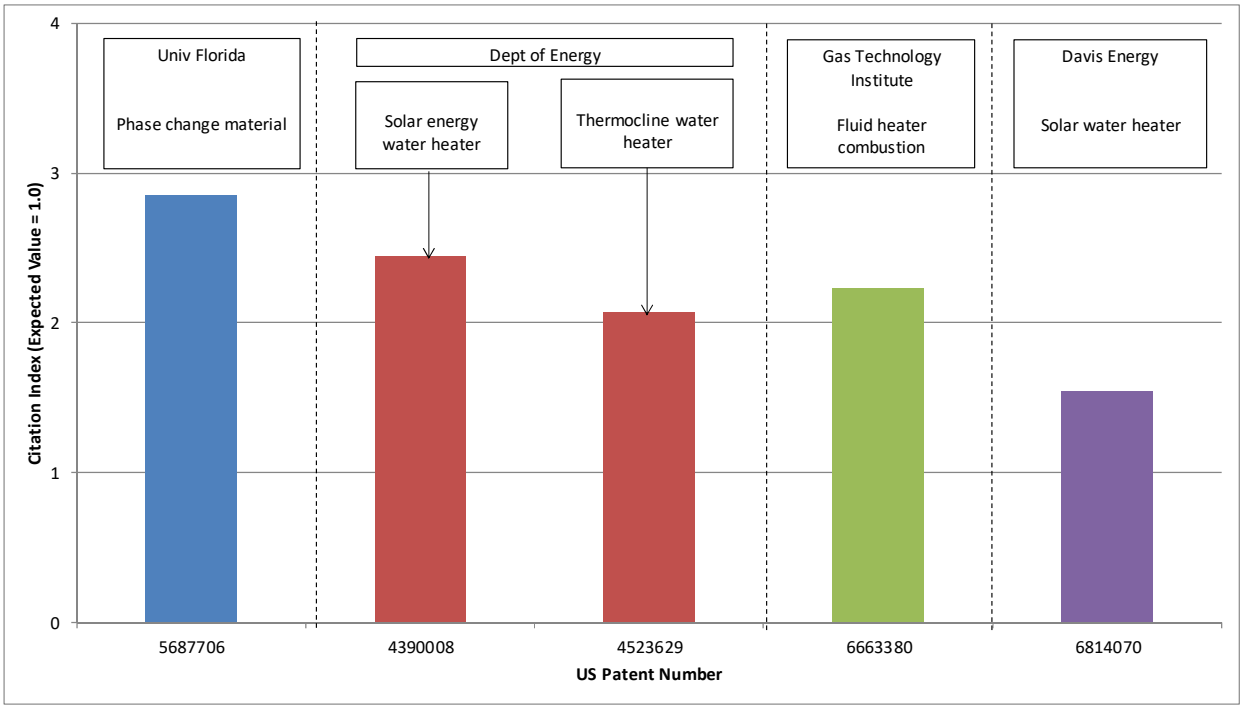
- Three of the leading companies have more than 5% of their water heating patent families linked via citations to earlier BTO-funded water heating patents. Paloma heads this list, with 6.9% of its patent families linked via citations to BTO-funded patents, followed by Navien (5.6%) and United Technologies (5.2%).

- BTO-funded water heating patents have a Citation Index of 1.08 (the Citation Index is a normalized citation metric with an expected value of 1.0; a value of 1.08 shows that, based on their age and technology, BTO-funded water heating patents have been cited as prior art 8% more frequently than expected by subsequent patents). This puts BTO-

funded patents in second place among the leading companies, behind only United Technologies. These are the only two patent portfolios with a Citation Index above one. This suggests that BTO-funded water heating patents have had a moderately strong overall influence on subsequent innovations.

- There are a number of individual high-impact BTO-funded water heating patents, examples of which are shown in Figure WH-E3. They include a 1997 University of Florida patent (US #5,687,706) that describes water heaters employing phase change materials to store heat. This patent has been cited as prior art by 47 subsequent patents, almost three times as many citations as expected given its age and technology. They also include a 1983 patent assigned to DOE related to solar energy water heaters (US #4,390,008), which has been cited as prior art by 25 subsequent patents, more than twice as many as expected. More recent highly-cited patents include a 2003 Gas Technology Institute patent for improved fluid heat combustion, and a 2004 Davis Energy patent describing a solar water heater.

Figure WH-E3 – Examples of Highly-Cited BTO-funded Water Heating Patents



1. Introduction

This report focuses on building technologies.[1] Its objective is to trace the technological influence of building technologies research funded by the Building Technologies Office (BTO) in the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE) and its precursor programs – as well as building technologies research funded by other offices in DOE. The purpose of the report is to:

(i) Locate patents awarded for key BTO-funded (and Other DOE-funded) innovations in building technologies; and
(ii) Determine the extent to which BTO-funded (and Other DOE-funded) building technologies research has influenced subsequent developments both within and beyond building technologies.

The primary focus of the report is on the influence of BTO-funded building technologies patents. That said, there are also other DOE-funded building technologies patents not linked to BTO funding. Rather than discard these patents, we instead include them in the analysis in a separate "Other DOE-funded" category. This enables us to examine the influence of BTO itself on the development of building technologies, while also tracing the influence of DOE more generally.

This report contains three main sections. The first of these sections describes the project design. This section includes a brief overview of patent citation analysis, and outlines its use in the multi-generation tracing employed in this project. The second section outlines the methodology, and includes a description of the various data sets used in the analysis, and the processes through which these data sets were constructed and linked.

The third section of the report presents the results of our analysis. This section is divided into three sub-sections, in turn containing the findings related to heating, ventilation and air conditioning (HVAC), appliances, and water heating. Within each sub-section, results are presented at the organizational level for both BTO-funded and Other DOE-funded patents. These results show the distribution of BTO-funded (and Other DOE-funded) patents across building technologies (as defined by Cooperative Patent Classifications). They also evaluate the extent of BTO's influence (and DOE's influence in general) on subsequent developments within and beyond building technologies. Patent level results are then presented to highlight individual BTO-funded building technologies patents that have been particularly influential, as well as to reveal key patents from other organizations that build extensively on BTO-funded building technologies research.[2]

[1] There are three technologies covered by this report: heating, ventilation and air conditioning (HVAC); appliances; and water heating. These are considered to be separate technologies. Each is analyzed individually, and the report contains separate results sections for the three technologies. That said, we use the shorthand "building technologies" in the Introduction, Project Design and Methodology sections of the report, rather than referring repeatedly to the more cumbersome "HVAC, appliances and water heating technologies".

[2] This is one of a series of similar reports examining research portfolios across a range of DOE offices. Note that the results are not designed to be compared across portfolios, for example in terms of numbers of patents granted, number of citations received etc. The portfolios have very different profiles with respect to research risks, funding levels and time periods covered, plus there are wide variations in the propensity to patent across technologies. Hence, the results reported in the various reports should not be used for comparative analyses across portfolios.

2. Project Design

This section of the report outlines the project design. It begins with a brief overview of patent citation analysis, which forms the basis for much of the evaluation presented in this report. This overview is followed by a description of the techniques used to link the various patent sets in the analysis, along with a listing and description of the metrics employed in the study.

The analysis described in this report is based largely upon tracing citation links between successive generations of patents. This tracing is carried out both backwards and forwards in time. The primary purpose of the backward tracing is to determine the extent to which innovations associated with leading companies in building technologies have used BTO-funded research as a foundation. Meanwhile, the primary purpose of the forward tracing is to examine how BTO-funded building technologies patents have influenced subsequent technological developments more broadly, both within and outside building technologies. Many elements of both the backward and forward tracing are also extended to the Other DOE-funded patents, in order to trace their influence, both overall and on the leading building technologies companies.[3]

Our analysis covers patents filed in three systems: the U.S. Patent & Trademark Office (U.S. patents); the European Patent Office (EPO patents); and the World Intellectual Property Organization (WIPO patents). By covering multiple generations of citations across patent systems, our analysis allows for a wide variety of possible linkages between DOE-funded building technologies research and subsequent technological developments. Examining all of these linkage types at the level of entire technologies involves a significant data processing effort, and requires access to specialist citation databases, such as those maintained at 1790 Analytics. As a result, this project is more ambitious than many previous attempts to trace through multiple generations of research, which have often been based on studying very specific technologies or individual products.

Patent Citation Analysis

In many patent systems, patent documents contain a list of references to prior art. The purpose of these prior art references is to detail the state of the art at the time of the patent application, and to demonstrate how the new invention is original over and above this prior art. Prior art references may include many different types of public documents. A large number of the references are to earlier patents, and these references form the basis for this study. Other references (not covered in this study) may be to scientific publications and other types of documents, such as technical reports, magazines and newspapers.

The responsibility for adding prior art references differs across patent systems. In the U.S. patent system, it is the duty of patent applicants to reference (or "cite") all prior art of which they are aware that may affect the patentability of their invention. Patent examiners may then reference

[3] The analyses described in this report were carried out separately for BTO-funded and Other DOE-funded patents in each of the three technologies. However, referring repeatedly to "BTO-funded/Other DOE-funded patents" or "BTO-funded/Other DOE-funded research" in describing the analyses is lengthy, so we instead use the collective terms "DOE-funded patents" and "DOE-funded research" in the Project Design and Methodology sections of the report.

additional prior art that limits the claims of the patent for which an application is being filed. In contrast to this, in patents filed at the European Patent Office (EPO) and World Intellectual Property Organization (WIPO), prior art references are added solely by the examiner, rather than by both the applicant and examiner. The number of prior art references on EPO and WIPO patents thus tends to be much lower than the number on U.S. patents.[4]

Patent citation analysis focuses on the links between generations of patents that are made by these prior art references. In simple terms, this type of analysis is based upon the idea that the prior art referenced by patents has had some influence, however slight, upon the development of these patents. The prior art is thus regarded as part of the foundation for the later inventions.

In assessing the influence of individual patents, citation analysis centers on the idea that highly cited patents (i.e. those cited by many later patents) tend to contain technological information of particular interest or importance. As such, they form the basis for many new innovations and research efforts, and so are cited frequently by later patents. While it is not true to say that every highly cited patent is important, or that every infrequently cited patent is necessarily trivial, many research studies have shown a correlation between patent citations and measures of technological and economic importance. For background on the use of patent citation analysis, including a summary of validation studies supporting its use, see: Breitzman A. & Mogee M. "The many applications of patent analysis", *Journal of Information Science*, 28(3), 2002, 187-205; and Jaffe A. & de Rassenfosse G. "Patent Citation Data in Social Science Research: Overview and Best Practices", NBER Working Paper No. 21868, January 2016.

Patent citation analysis has also been used extensively to trace technological developments over time. For example, in the analysis presented in this report, we use citations from patents to earlier patents to trace the influence of DOE-funded building technologies research. Specifically, we identify cases where patents cite DOE-funded building technologies patents as prior art. These represent first-generation links between DOE-funded patents and subsequent technological developments. We also identify cases where patents cite patents that in turn cite DOE-funded building technologies patents. These represent second-generation links between technological developments and DOE-funded research.

The idea behind this analysis is that the later patents have built in some way on the earlier DOE-funded building technologies research. By determining how frequently DOE-funded building technologies patents have been cited by subsequent patents, it is thus possible to evaluate the extent to which DOE-funded research forms a foundation for innovations both within and beyond building technologies.

[4] Note that this analysis does not cover patents from other systems, notably patents from the Chinese, Japanese and Korean patent offices. This is because patents from these systems do not typically list any prior art. Hence, it is not possible to use citation links to trace the influence of DOE research on patents from these systems. Having said this, Chinese, Japanese and Korean organizations are among the most prolific applicants in the WIPO system. Our analysis thus picks up the role of organizations from these countries via their WIPO filings.

Backward and Forward Tracing

As noted above, the purpose of this analysis is to trace the influence of DOE-funded building technologies research upon subsequent developments both within and beyond building technologies. There are two approaches to such a tracing study – backward tracing and forward tracing – each of which has a slightly different objective. Backward tracing, as the name suggests, looks backwards over time. The idea of backward tracing is to take a particular technology, product, or industry, and to trace back to identify the earlier technologies upon which it has built. In the context of this project, we first identify the leading building technologies organizations in terms of patent portfolio size. We then trace backwards from the patents owned by these organizations. This makes it possible to determine the extent to which innovations associated with these leading building technologies organizations build on earlier BTO-funded and Other DOE-funded research.

The idea of forward tracing is to take a given body of research, and to trace the influence of this research upon subsequent technological developments. In the context of the current analysis, forward tracing involves identifying all building technologies patents resulting from research funded by DOE (i.e. BTO plus Other DOE). The influence of these patents on later generations of technology is then evaluated. This tracing is not restricted to subsequent building technologies patents, since the influence of a body of research may extend beyond its immediate technology. Hence, the purpose of the forward tracing element is to determine the influence of DOE-funded building technologies patents on developments both inside and outside these technologies.

Tracing Multiple Generations of Citation Links

The simplest form of tracing study is one based on a single generation of citation links between patents. Such a study identifies patents that cite, or are cited by, a given set of patents as prior art. The analysis described in this report extends the tracing by adding a second generation of citation links.[5] The backward tracing starts with patents assigned to the leading patenting organizations in building technologies. The first generation contains the patents that are cited as prior art by these starting patents. The second generation contains patents that are in turn cited as prior art by these first generation patents. In other words, the backward tracing starts with building technologies patents owned by leading organizations in these technologies, and traces back through two generations of earlier patents to identify the technologies upon which they were built, including those funded by DOE. The forward tracing starts with DOE-funded patents in building technologies. The first generation contains the patents that cite these DOE-funded patents as prior art. The second generation contains the patents that in turn cite these first-generation patents. In other words, the analysis starts with DOE-funded building technologies patents and traces forward for two generations of subsequent patents.

This means that we trace forward through two generations of citations starting from DOE-funded building technologies patents; and backward through two generations starting from the patents owned by leading building technologies organizations. Hence there are two types of links between DOE-funded patents and subsequent generations of patents:

[5] As noted above, the forward and backward tracing were carried out separately for BTO-funded and Other DOE-funded building technologies patents. The references in this section to "DOE patents" are shorthand, and do not mean that the tracing was carried out for all DOE-funded building technologies patents as a single portfolio.

1. **Direct Links**: a patent cites a DOE-funded building technologies patent as prior art.
2. **Indirect Links**: a patent cites an earlier patent, which in turn cites a DOE-funded building technologies patent. The DOE patent is thus linked indirectly to the later patent.

The idea behind adding the second generation of citations is that agencies such as DOE often support basic scientific research. It may take time, and numerous generations of research, for this basic research to be used in an applied technology, for example that described in a patent owned by a leading company. Introducing a second generation of citations provides greater access to these indirect links between basic research and applied technology. That said, one potential problem with adding generations of citations must be acknowledged. Specifically, if one uses enough generations of links, eventually almost every node in the network will be linked. This is a problem common to many networks, whether these networks consist of people, institutions, or scientific documents, as in this case. The most famous example of this is the idea that every person is within six links of any other person in the world. By the same logic, if one takes a starting set of patents, and extends the network of citations far enough, almost all patents will be linked to this starting set. Hence, while including a second generation of citations provides insights into indirect links between basic research and applied technologies, adding further generations may bring in too many patents with little connection to the starting patent set.

Constructing Patent Families

The coverage of a patent is limited to the jurisdiction of its issuing authority. For example, a patent granted by the U.S. Patent & Trademark Office (a 'U.S. patent') provides protection only within the United States. If an organization wishes to protect an invention in multiple countries, it must file patents in each of those countries' systems. For example, a company may file to protect a given invention in the U.S., China, Germany, Japan and many other countries. This results in multiple patent documents for the same invention.[6] Also, in some systems – notably the U.S. – inventors may apply for a series of patents based on the same underlying invention.

In the case of this study, one or more U.S., EPO and WIPO patents may result from a single invention. To avoid counting the same inventions multiple times, it is necessary to construct "patent families". A patent family contains all of the patents and patent applications that result from the same original patent application (named the "priority application"). A family may include patents from multiple countries, and also multiple patents from the same country. In this project, we constructed patent families for DOE-funded building technologies patents, and also for the patents owned by leading building technologies organizations. We also assembled families for all patents linked via citations to DOE-funded building technologies patents.

To construct these patent families, we matched the priority documents of the U.S., EPO and WIPO patents, in order to group them into the appropriate families. It should be noted that the priority document need not necessarily be a U.S., EPO or WIPO application. For example, a Japanese patent application may result in U.S., EPO and WIPO patents, which are grouped in the same patent family because they share the same Japanese priority document.

[6] It also means that patents from a given country's system are not synonymous with inventions made in that country. Indeed, roughly half of all U.S. patent applications are from overseas inventors.

Metrics Used in the Analysis

Table 2-1 contains a list of the metrics used in the analysis. These metrics are divided into three main groups – technology landscape metrics (trends, assignees, and technology distributions), backward tracing metrics, and forward tracing metrics. Findings for each of these three groups of metrics can be found in the Results section of the report.

Table 2-1 – List of Metrics Used in the Analysis

Metric
Trends
• No. of BTO/Other DOE-funded building technologies patent families by year of priority application
• No. of BTO/Other DOE-funded granted U.S. building technologies patents by issue year
• Overall number of building technologies patent families by priority year
• Percentage of building technologies patents families funded by BTO/Other DOE by priority year
Assignee Metrics
• No. of building technologies patent families for leading patenting organizations
• Assignees with largest number of building technologies patent families funded by BTO/Other DOE
Technology Metrics
• Patent classification (CPC) distribution for BTO-funded building technologies patent families (vs Other DOE-funded, leading building technologies companies, all building technologies patents)
Backward Tracing Metrics
• No. of leading company building technologies patent families linked via citations to earlier patent families from BTO/Other DOE and other leading companies
• No. of building technologies patent families for each leading company linked via citations to earlier BTO/Other DOE-funded patent families
• Total citation links from each leading company to BTO/Other DOE-funded patent families
• Percentage of leading company building technologies patent families linked via citations to earlier BTO/Other DOE-funded patent families
• BTO/Other DOE-funded building technologies patent families linked via citations to largest number of leading company building technologies patent families
• Leading company building technologies patent families linked via citations to largest number of BTO-funded building technologies patent families
• Highly cited leading company building technologies patent families linked via citations to earlier BTO-funded building technologies patent families
Forward Tracing Metrics
• Citation Index for building technologies patent portfolios owned by leading companies, plus portfolios of BTO/Other DOE-funded building technologies patents
• No. of patent families linked via citations to BTO/Other DOE-funded building technologies patents by patent classification
• Organizations (beyond leading building technologies companies) linked via citations to largest number of BTO/Other DOE funded building technologies patent families
• Highly cited BTO-funded building technologies U.S. patents
• BTO/Other DOE-funded building technologies patent families linked via citations to largest number of subsequent building technologies/other patent families
• Highly cited patents (not owned by leading companies) linked via citations to earlier BTO-funded building technologies patents families

3. Methodology

The previous section of the report outlines the objective of our analysis – that is, to determine the influence of BTO-funded (and Other DOE-funded) building technologies research on subsequent developments both within and outside building technologies. This section of the report describes the methodology used to implement the analysis. Particular emphasis is placed on the processes employed to construct the various data sets required for the analysis. Specifically, the backward tracing starts from the set of all building technologies patents owned by leading patenting organizations in these technologies. Meanwhile, the forward tracing starts from the sets of building technologies patents funded by BTO and Other DOE. We therefore had to define these various data sets – BTO-funded building technologies patents; Other DOE-funded building technologies patents; and building technologies patents assigned to the leading organizations.

Identifying BTO-funded and Other DOE-funded Building Technologies Patents

The objective of this analysis is to trace the influence of building technologies research funded by BTO (plus building technologies research funded by the remainder of DOE) upon subsequent developments both within and outside building technologies. Outlined below are the three steps used to identify BTO-funded and Other DOE-funded building technologies patents. These three steps are:

(i) Defining the universe of DOE funded patents;

(ii) Determining which of these DOE funded patents are relevant to building technologies; and

(iii) Categorizing these DOE-funded building technologies patents according to whether or not they can be linked definitively to BTO funding.

Defining the Universe of DOE-Funded Patents

Identifying patents funded by government agencies is often more difficult than locating 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 seventeen national laboratories. Patents emerging from these laboratories may be assigned to DOE. However, they may also be assigned to the organization that manages a given laboratory. For example, many patents from Sandia National Laboratory are assigned to Lockheed Martin (Sandia's former lab manager), while many Lawrence Livermore National Laboratory patents are assigned to the University of California. Lockheed Martin and the University of California are large organizations with many interests beyond managing DOE labs, so one cannot simply define all of the patents assigned to them as DOE-funded. A further complication is that DOE

does not only fund research in its own labs and research centers, but also extramural research carried out by other organizations. If this research results in patented inventions, these patents are likely to be assigned to the organizations carrying out the research, rather than to DOE.

We therefore constructed a database containing all DOE-funded patents. These include patents assigned to DOE itself, and also patents assigned to individual labs, lab managers, and other organizations and companies funded by DOE. This "All DOE" patent database was constructed using a number of sources:

1. ***DOEPatents 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 patents that resulted from these DOE grants.

2. ***iEdison Database*** – EERE staff provided us with an output from the iEdison database, which is used by government grantees and contractors to report government-funded subject inventions, patents, and utilization data to the government agency that issued the funding award.

3. ***Visual Patent Finder Database*** – EERE also provided us with an output from its Visual Patent Finder tool. This tool takes DOE-funded patents and clusters them based on word occurrence patterns. In our case, the output was a flat file of DOE-funded patents.

4. ***Patents assigned to DOE*** – in the USPTO database, we identified a small number of U.S. patents assigned to DOE itself that were not in the any of the sources above. These patents were added to the list of DOE patents.

5. ***Patents with DOE Government Interest*** – A U.S. patent has on its front page a section entitled 'Government Interest', which details the rights that the government has in a particular invention. For example, if a government agency funds research at a private company, the government may have certain rights to patents granted based on this research. We identified all patents that refer to 'Department of Energy' or 'DOE' in their Government Interest field, including different variants of these strings. We also identified patents that refer to government contracts beginning with 'DE-' or containing the string '-ENG-'. The former string typically denotes DOE contracts and financial assistance projects, while the latter is a legacy code listed on a number of older DOE-funded patents. We manually checked all of the patents containing these strings that were not already in any of the sources above, to make sure that they are indeed DOE-funded (e.g. '-ENG-' is also used in a small number of NSF contracts). We then included any additional DOE funded patents in the database.

The "All DOE" patent database constructed from these five sources contains more than 31,000 U.S. patents issued between January 1976 and December 2018 (the end-point of the primary data collection for this analysis).

Identifying DOE-Funded Building Technologies Patents

Having defined the universe of DOE-funded patents, the next step was to determine which of these patents are relevant to building technologies. We designed custom patent filters to identify building technologies patents that may be funded by either BTO or a different office within DOE. These filters consist of a combination of Cooperative Patent Classifications (CPCs) and keywords. Details of the patent filters are shown in Table 3-1 (HVAC), Table 3-2 (Appliances) and Table 3-3 (Water Heating).

The HVAC filter in Table 3-1 consists of three elements. The form of the filter is (Filter A OR Filter B) NOT Filter C. That is, patents are selected if they qualify under either Filter A or Filter B. Patents that qualify under Filter C are then removed, since these patents are directed to vehicle applications of HVAC.

Table 3-1 – Filters used to Identify HVAC Patents

Filter A
Cooperative Patent Classification
F24F – Air conditioning/ventilation
F24D 1-15 – Space heating and central heating systems
F24D 19 – Central heating system details
F24D 2220 – Domestic heat energy sources
F24H 3 – Air heaters
F24H 9/0052-0078 – Air heater details
F24H 9/1854-189 – Air heater drainage
F24H 9/2064-2092 – Air heater safety devices
Y02B 10/24 – Air conditioning systems
Y02B 30 – Energy efficient HVAC
Y02P 60/147 – Energy efficient HVAC
OR
Filter B
Cooperative Patent Classification
F25 – Refrigeration and cooling
F28 – Heat exchange
AND
Title/Abstract
Air(?)condition* or ventilat* or HVAC
NOT
Filter C
Cooperative Patent Classification
B60H – Heating/cooling for vehicles
OR
Title/Abstract
Car or cars or vehicle* or automobile*

Table 3-2 contains the filter used to identify appliance patents. This filter consists of six elements, each directed to a different type of appliance. Each element contains combinations of CPCs and keywords, connected by various Boolean logic expressions (AND, OR, NOT). The overall form of the filter is Filter A OR Filter B …. OR Filter F. That is, patents are selected if they qualify under any of the six elements.

Table 3-2 – Filters used to Identify Appliance Patents

Filter A (Refrigerators)
CPC = F25D 11 (Domestic refrigerators) or Y02B 40/30-34 (Energy efficient refrigerators) OR (CPC = F25D (Refrigerators) and Title/Abstract = (domestic* or house(?)hold*))
Filter B (Dishwashers)
CPC = A47L 15 (Washing machines for crockery or tableware) or Y02B 40/40-46 (Energy efficient dishwashers) OR (CPC = B08B 3 (Cleaning using liquid/steam) and Title/Abstract = (dish(?)wash* or wash*(?)dish*))
Filter C (Washing Machines)
(CPC = D06F 9-39 (Washing machines for textile articles) NOT (CPC = A47L 15 (Washing machines for crockery or tableware)) OR D06F 2202-2232 (Washing machine control) or Y02B 40/50-58 (Energy efficient washing machines)
Filter D (Dryers)
(CPC = D06F 49 (Domestic spin dryers) or D06F 58 (Domestic laundry dryers)) or Y02B 40/70-74 (Energy efficient dryers)) NOT CPC = A47L 15 (Washing Machines for Crockery or Tableware)
Filter E (Stoves)
CPC = (F24C (Domestic stoves/ranges) AND Title/Abstract = (hob* or oven* or range* or stove* or cook(?)top*) OR CPC=Y02B 40/10-126, 16-18 (Energy efficient domestic cooking)
Filter F (Microwaves)
CPC = F24C 7/02 (Stoves using microwaves) or Y02B 40/14-146 (Energy efficient microwaves) OR (CPC = H05B 6/64-80 (Heating using microwaves) and Title/Abstract = (food* or oven* or cook*)) OR (CPC = F24C (Domestic stoves/ranges) and Title/Abstract = micro(?)wave*)

Table 3-3 contains the filters used to identify water heating patents. This filter consists of three elements, and the form of the filter is (Filter A OR Filter B) NOT Filter C. That is, patents are selected if they qualify under either Filter A or Filter B. Patents that qualify under Filter C are then removed, since these patents are directed to domestic appliances (such as coffee makers and kettles) and vehicle heating applications.

Table 3-3 – Filters used to Identify Water Heating Patents

Filter A
Cooperative Patent Classification
F24D 17 – Domestic hot water supply systems
F24H 1 – Water heaters
F24H 4 – Fluid heaters using heat pumps
F24H 6 – Combined water and air heaters
F24H 7 – Storage heaters
F24H 9/0005-047 – Water heater details
F24H 9/122-128 – Water heating pipes
F24H 9/1809-1845 – Water heating elements
F24H 9/2007-2057 – Water heating safety devices
OR
Filter B
Cooperative Patent Classification
F24 – Heating
F25 – Refrigeration and cooling
F28 – Heat Exchange
AND
Title/Abstract
(Boiler* or Water(?)heat*) AND (domestic* or house(?)hold* or central(?)heat*)
NOT
Filter C
Cooperative Patent Classification
A47 – Domestic appliances
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*

Having generated patent lists using the filters in Tables 3-1 – Table 3-3, we then sent these lists to BTO for review. After incorporating feedback from BTO, we adjusted the patent sets, resulting in the initial lists of building technologies granted U.S. patents funded by DOE. The initial HVAC list contained 183 patents, while the appliances list contained 70 patents and the water heating list 35 patents.

Defining BTO-funded vs. Other DOE-funded Building Technologies Patents

As noted above, linking DOE-funded patents to individual offices is often a difficult task. For this analysis, EERE staff undertook an exhaustive process to determine which of the 183 DOE-funded HVAC patents, 70 appliance patents and 35 water heating patents in the initial lists could be linked definitively to BTO funding. This process involved a number of steps, which are listed below:

(i) Linking contract numbers listed in patents to EERE project contract numbers, for financial assistance projects,
(ii) Linking contract numbers listed in patents to EERE SBIR project agreement numbers,
(iii) Asking BTO technology managers to verify individual patents,
(iv) Asking BTO technology managers to send lab patents to lab POCs to get direct verification of these patents,
(v) Contacting individual inventors listed on patents to ask them to confirm whether individual patents were funded by BTO, and
(vi) Locating references to patents in available office annual project progress reports or patent disclosure documents with accomplishments reported by PIs.

Final Lists of BTO-funded and Other DOE-funded Building Technologies Patents

Based on the process described above, we divided the initial lists of DOE-funded building technologies U.S. patents into two categories – BTO-funded and Other DOE-funded.[7] 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 U.S. patents that are continuations, continuations-in-part, or divisional applications of each of the patents in the final set. We then grouped the patents into families by matching priority documents (see earlier discussion of patent families). Table 3-4 contains a summary of the number of BTO-funded and Other DOE-funded HVAC, appliance and water heating patents and patent families. Each of these portfolios contains patents dating back to the mid-1970s, which is the starting point for the analysis presented in this report.

Table 3-4 – Number of BTO-funded and Other DOE-funded Building Technologies Patents and Patent Families

	# Patent Families	# U.S. Patents	# EPO Patents	# WIPO Patents
HVAC				
BTO-funded	113	134	23	33
Other DOE-funded	51	59	9	13
Total DOE-funded	164	193	32	46
Appliances				
BTO-funded	58	64	14	11
Other DOE-funded	8	8	0	0
Total DOE-funded	66	72	14	11
Water Heating				
BTO-funded	23	25	2	8
Other DOE-funded	10	10	0	4
Total DOE-funded	33	35	2	12

[7] As a result of this process, all patents were definitively characterized as BTO-funded or not BTO-funded. There were no "unknown" cases where there was uncertainty as to which category a patent should be assigned.

Table 3-4 shows that we identified a total of 113 BTO-funded HVAC patent families, containing 134 U.S. patents, 23 EPO patents, and 33 WIPO patents (see Appendix HV-A for patent list). We also identified 51 Other DOE-funded HVAC patent families, containing 59 U.S. patents, nine EPO patents, and 13 WIPO patents (see Appendix HV-B for patent list).

In addition, Table 3-4 shows that we identified a total of 58 BTO-funded appliance patent families, containing 64 U.S. patents, 14 EPO patents, and 11 WIPO patents (see Appendix AP-A for patent list). We also identified eight Other DOE-funded appliance patent families, containing eight U.S. patents, but no EPO or WIPO patents (see Appendix AP-B for patent list).

Table 3-4 also shows that we identified a total of 23 BTO-funded water heating patent families, containing 25 U.S. patents, two EPO patents, and eight WIPO patents (see Appendix WH-A for patent list). We also identified 10 Other DOE-funded water heating patent families, containing 10 U.S. patents, zero EPO patents, and four WIPO patents (see Appendix WH-B for patent list).

Identifying Building Technologies Patents Assigned to Leading Organizations

The purpose of the backward tracing element of our analysis is to evaluate the influence of BTO-funded (and Other DOE-funded) research upon building technologies innovations produced by leading organizations in these technologies. To identify such organizations, we first defined the universes of HVAC, appliance and water heating patents in the period 1976-2018 using the patent filters detailed earlier in Table 3-1 – Table 3-3.

Based on the filter in Table 3-1, we identified a total of 24,514 HVAC U.S. patents, 21,817 HVAC EPO patents, and 22,768 HVAC WIPO patents. We grouped these patents into 51,821 patent families by matching priority documents. We then located the most prolific patenting organizations in this overall HVAC patent universe, based on number of patent families. The ten organizations with the largest number of HVAC patent families are shown in Table 3-5.

Table 3-5 – Top 10 Patenting HVAC Organizations

Organization	# HVAC Patent Families
Mitsubishi Electric	3367
Daikin Industries	1744
United Technologies	1411
LG Electronics	1361
Panasonic	1297
Honeywell International	647
Samsung Electronics	611
Bosch	604
Johnson Controls	475
Toshiba	468

Based on the filter in Table 3-2, we identified a total of 16,866 appliance U.S. patents, 19,918 appliance EPO patents, and 14,950 appliance WIPO patents. We grouped these patents into 35,876 patent families by matching priority documents. We then located the most prolific patenting organizations in this overall appliance patent universe, based on number of patent

families. The ten organizations with the largest number of appliance patent families are shown in Table 3-6.

Table 3-6 – Top 10 Patenting Appliance Organizations

Organization	# Appliance Patent Families
Bosch	4117
Whirlpool	3071
LG Electronics	2753
Electrolux	2740
Samsung Electronics	1424
Haier	1384
Koc Holding	1351
Panasonic	1021
General Electric	840
Miele & Cie	788

Based on the filter in Table 3-3, we identified a total of 3,731 water heating U.S. patents, 3,929 water heating EPO patents, and 3,273 water heating WIPO patents. We grouped these patents into 8,340 patent families by matching priority documents. We then located the most prolific patenting organizations in this overall water heating patent universe, based on number of patent families. The ten organizations with the largest number of water heating patent families are shown in Table 3-7.

Table 3-7 – Top 10 Patenting Water Heating Organizations

Organization	# Water Heating Patent Families
Bosch	286
A.O. Smith	229
Mitsubishi Electric	216
Vaillant	166
Paloma Industries	145
Kyung Dong Navien	107
Panasonic	97
Daikin Industries	79
United Technologies	77
Viessmann	69

The numbers of patent families listed in Tables 3-5 – Table 3-7 include all variant names under which each organization has patents, taking into account subsidiaries and acquisitions.[8] The HVAC, appliance and water heating patent families of these companies form the starting point for the backward tracing element of the analysis in the respective technologies. As such, this analysis evaluates the influence of BTO-funded and Other DOE-funded building technologies research on innovations associated with the leading companies in these technologies.

[8] All ten of the organizations in each of Tables 6-8 are companies. For clarity, they are referred to in the results section of the report as the leading HVAC, appliance and water heating companies, rather than organizations. Also, note that they are selected based on patent portfolio size, which does not necessarily reflect number of units sold or revenues, profits etc. A fuller description would be the leading patenting HVAC, appliance and water heating companies, but this is a cumbersome description to use throughout the results section of the report.

Constructing Citation Links

Through the processes described above, we constructed starting patent sets for both the backward and forward tracing elements of the analysis. The patent sets for the backward tracing consisted of patent families assigned to the leading patenting organizations in HVAC, appliance and water heating technologies. The patent sets for the forward tracing consisted of BTO-funded (and, separately, Other DOE-funded) HVAC, appliance and water heating patent families.

Having defined these patent sets, we then traced backward through two generations of citations from the leading organizations' building technologies patents, and forward through two generations of citations from the BTO/Other DOE-funded building technologies patents. These included citations listed on U.S., 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 described in the next section of this report. These results are reported first for HVAC, followed by appliances, and then water heating.

4. Results – HVAC

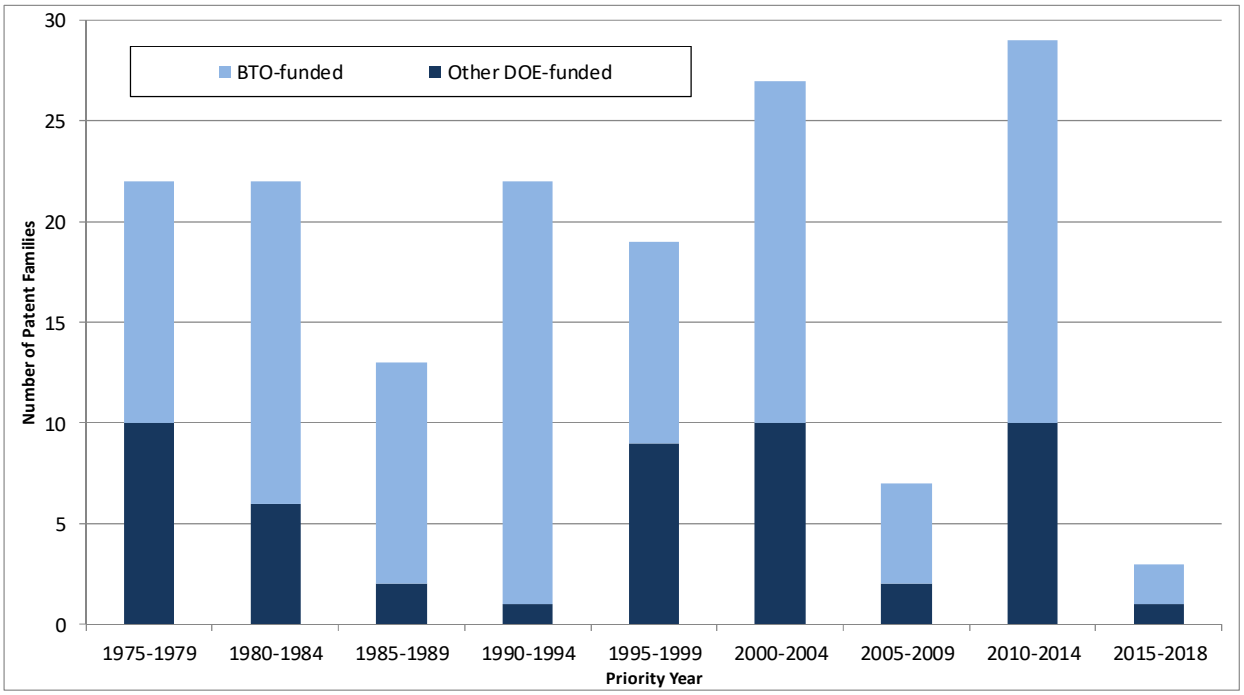
This section of the report outlines the results of our analysis tracing the influence of BTO-funded and Other DOE-funded HVAC research on subsequent developments both within and beyond HVAC technology. The results are divided into three main sections. In the first section, we examine trends in patenting over time in HVAC, and assess the distribution of BTO-funded and Other DOE-funded patents across HVAC technologies. The second section then reports the results of an analysis tracing backwards from HVAC patents owned by the leading companies in this technology. The purpose of this analysis is to determine the extent to which HVAC innovations developed by leading companies build upon earlier HVAC research funded by BTO (plus HVAC research funded by the remainder of DOE). In the third section, we report the results of an analysis tracing forwards from BTO-funded (and Other DOE-funded) HVAC patents. The purpose of this analysis is to assess the broader influence of DOE-funded research upon subsequent developments within and beyond HVAC technology.

Overall Trends in HVAC Patenting

Trends in HVAC Patenting over Time

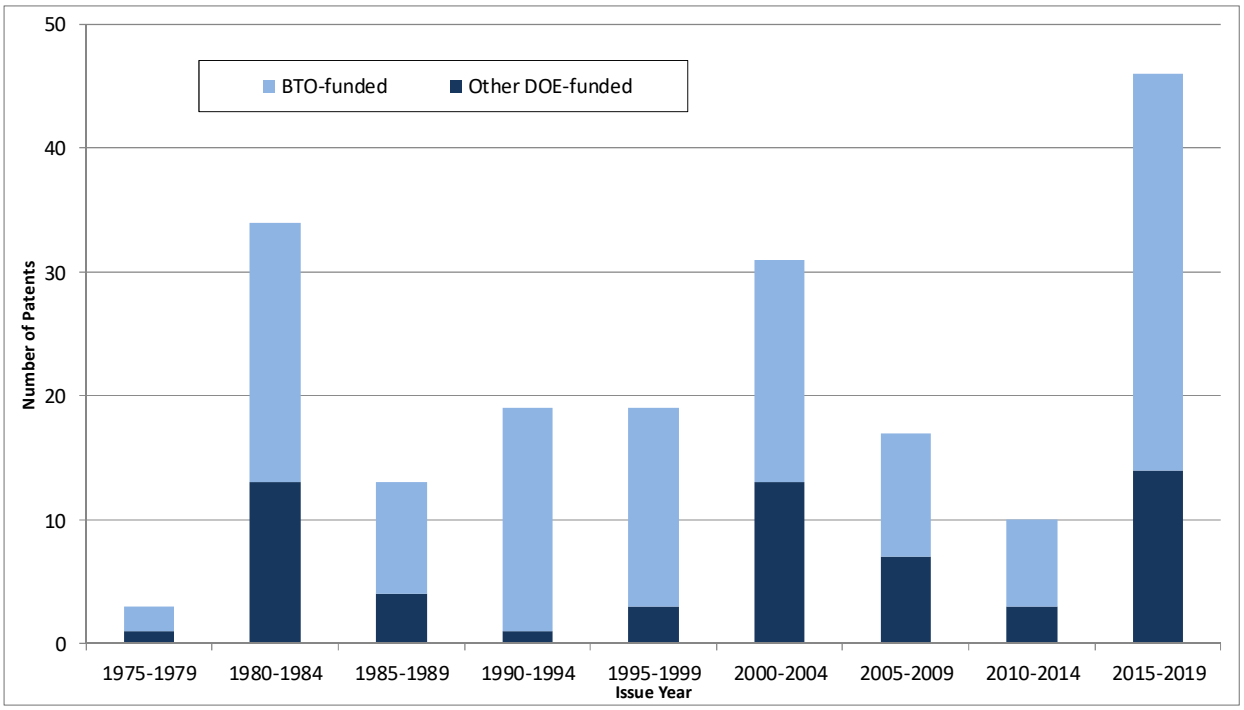
Figure 4-1 shows the number of DOE-funded HVAC patent families by priority year – i.e. the year of the first application in each patent family. This figure separates BTO-funded and Other DOE-funded patent families, with the former shown in light blue, and the latter in dark blue. Figure 4-1 shows no clear trend in DOE-funded HVAC patenting. There are five time periods with more than twenty patent families, the earliest in 1975-1979 and the latest in 2010-2014 (when the number of patent families peaked at 29). In amongst these five more active time periods are three periods with lower numbers of patent families (1985-1989 with 13 families; 1995-1999 with 19 families; and 2005-2009 with seven families – note that data for 2015-2018 are incomplete, as outlined below Figure 4-1). In all time periods, there are more BTO-funded patent families than Other DOE-funded families. The former represent a particularly high percentage of patent families between 1985 and 1994, and account for the majority if families in the more recent peak years of 2000-2004 and 2010-2014.

Figure 4-1 - Number of HVAC Patent Families funded by BTO and Other DOE Sources by Priority Year (5-Year Totals)



Note: The final time period in this figure is 2015-2018, and is shown for completeness, although data for this time period are incomplete. Our primary data collection covered only patents issued through 2018. Due to time lags associated with the patenting process, only a fraction of the patent families from 2015-2018 will be included.

Figure 4-2 - Number of DOE-Funded HVAC U.S. Patents by Issue Year (5-Year Totals)

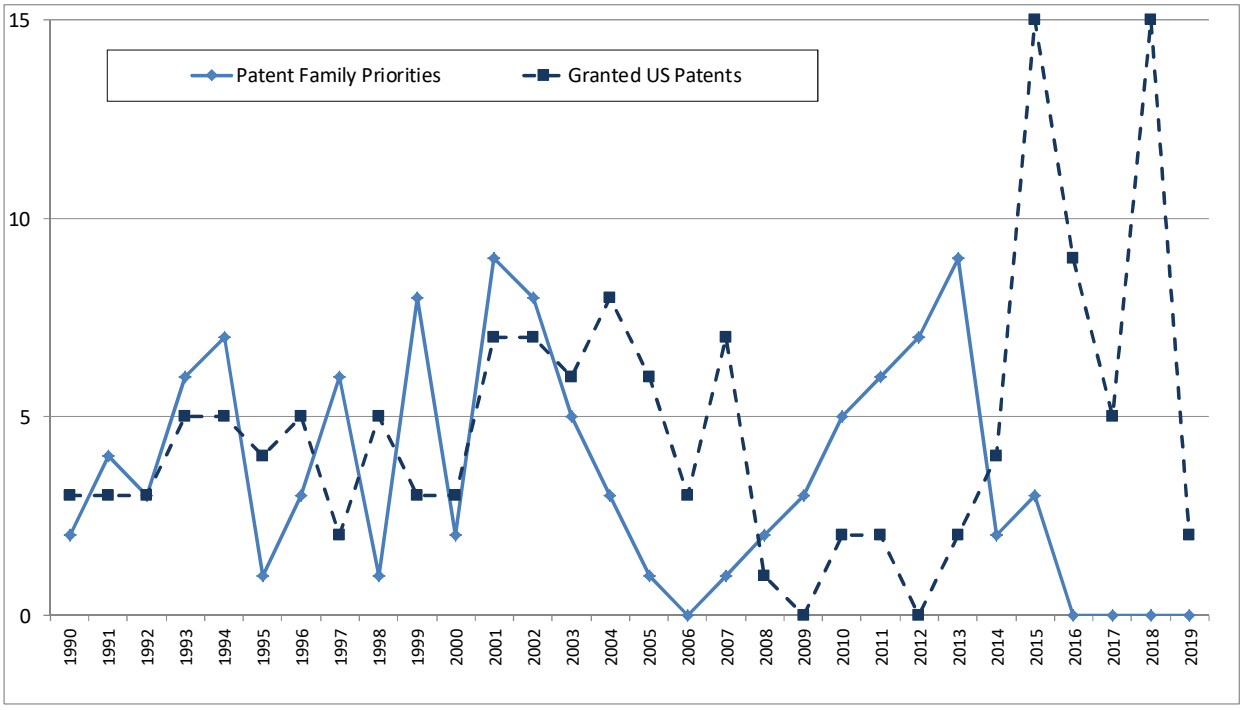


Note: The data collection period for this analysis ended with 2018. Any 2019 patents in the 2015-2019 column are additional patents that have been included because they are members of the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

Figure 4-2 shows the number of HVAC granted U.S. patents funded by DOE. This figure follows a similar pattern to Figure 4-1, which is based on patent family applications. There is again a lack of a consistent overall trend, with periods of active patenting interspersed with periods with many fewer patents. The peaks in the number of U.S. patents occurred in 1980-1984 (34 patents), 2000-2004 (31 patents) and 2015-2019 (46 patents). In each of the time periods, there were more BTO-funded patents than Other DOE-funded patents, with the former also representing the bulk of the patents in the 1990s, and in the most recent peak in 2015-2019.

Comparing Figures 4-1 and 4-2 shows the effect of time lags in the patenting process. For example, many of the patent families with priority dates in 2010-2014 (Figure 4-1) resulted in granted U.S. patents in 2015-19 (Figure 4-2). These time lags can also be seen in Figure 4-3, which shows patent family priorities alongside granted U.S. patents (BTO and Other DOE are combined in this figure, in order to simplify the presentation). This figure reveals that there were peaks in DOE-funded HVAC patent families in 1999 and 2001, resulting in a succession of granted U.S. patents between 2001 and 2007. More recently, there was in increase in DOE-funded HVAC patent families filed in the early 2010s, leading to spikes in U.S. patents in 2015 and 2018.

Figure 4-3 - Number DOE-funded HVAC Patent Families (by Priority Year) and Granted U.S. Patents (by Issue Year)

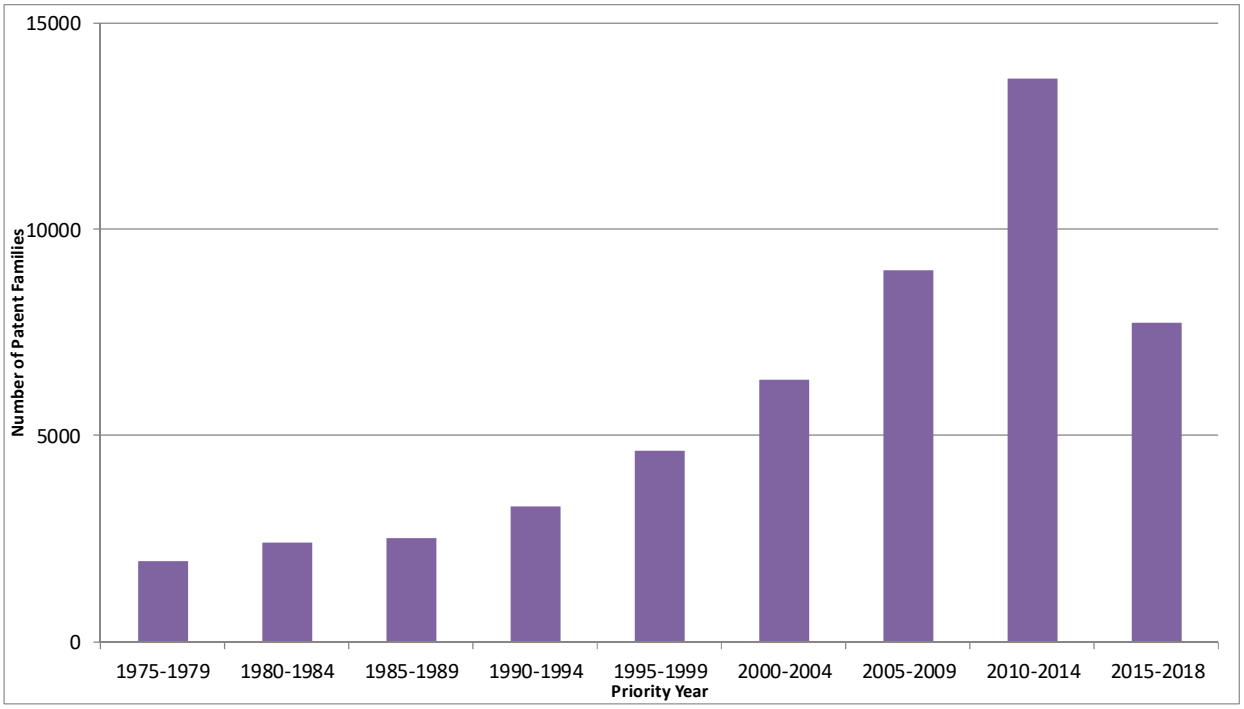


Note: The data collection period for this analysis ended with 2018. The 2019 patents are additional patents included because they are in the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

Figures 4-1 – 4-3 focus on DOE-funded HVAC patent families. Figure 4-4 broadens the scope, and shows the overall number of HVAC patent families by priority year (based on USPTO, EPO, and WIPO filings). This figure reveals a distinct trend in HVAC patenting over time. Between 1975 and 1989, the overall number of HVAC patent families was relatively consistent at 400-500

per year (i.e. 2000-2500 for each 5-year period). The number of patent families then started to increase in the 1990s, and continued to increase in the new century, peaking at 13,658 in 2010-2014 (i.e. there were more than five times as many patent families filed in 2010-2014 as there were in 1985-1989). The number of patent families declined to 7,720 in 2015-2018, although data for this time period are incomplete.

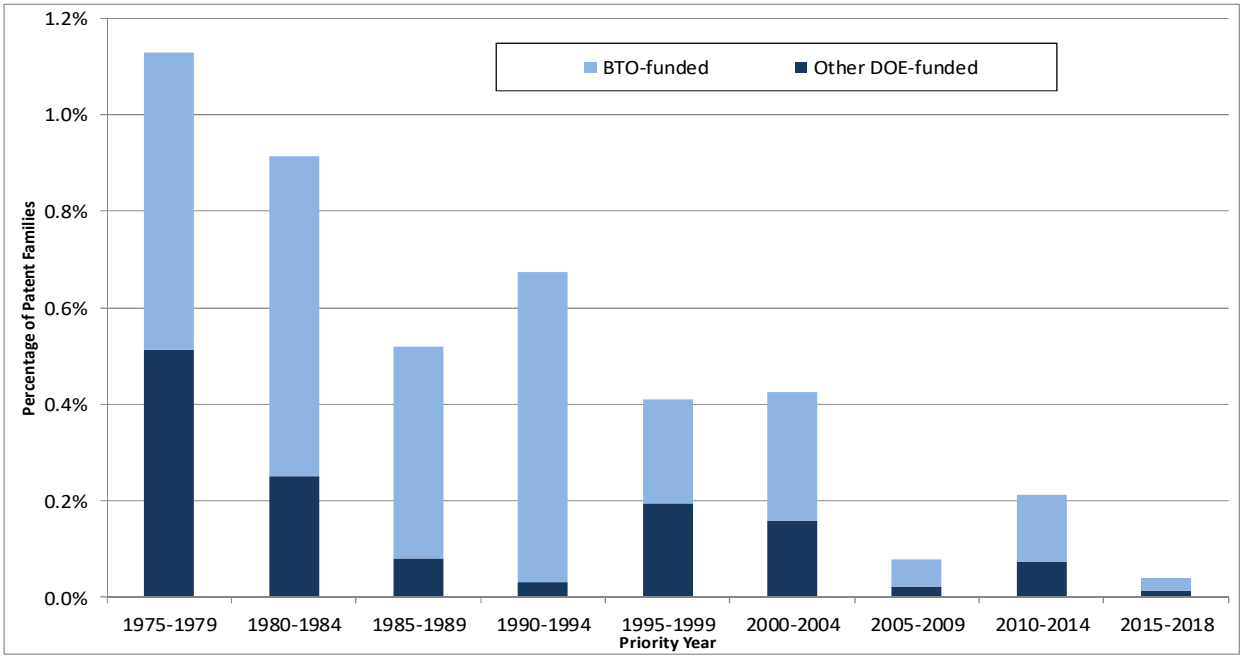
Figure 4-4 - Total Number of HVAC Patent Families by Priority Year (5-Year Totals)



Note: The final time period in this figure is 2015-2018. Data for this time period are incomplete. Due to time lags associated with the patenting process, only a fraction of the patent families from this time period will be included.

Figure 4-5 shows the percentage of HVAC patent families in each time period that were funded by DOE (BTO plus Other DOE). This figure reveals this percentage has declined over time, as overall HVAC patenting has increased while DOE-funded patenting has remained relatively consistent. The percentage of HVAC patent families funded by DOE peaked at 1.1% in 1975-1979 (with 0.6% funded by BTO). By 2010-2014, the percentage had declined to 0.2%. Such a decline is not surprising given the growth in overall HVAC patenting from 1990 onwards, with DOE representing only one source of funding, alongside the R&D budgets of numerous very large companies. Overall, DOE-funded patent families represent 0.32% of the total number of HVAC families in the period 1976-2018.

Figure 4-5 - Percentage of HVAC Patent Families Funded by DOE by Priority Year



Note: The final time period in this figure is 2015-2018. Data for this time period are incomplete. Due to time lags associated with the patenting process, only a fraction of the patent families from this time period will be included.

Leading HVAC Patent Assignees

The ten leading patenting companies in HVAC technology are listed above in Table 3-5, along with their number of HVAC patent families. Figure 4-6 shows the same information in graphical form, while also including DOE-funded patent families.

Figure 4-6 – Leading HVAC Companies (based on number of patent families)

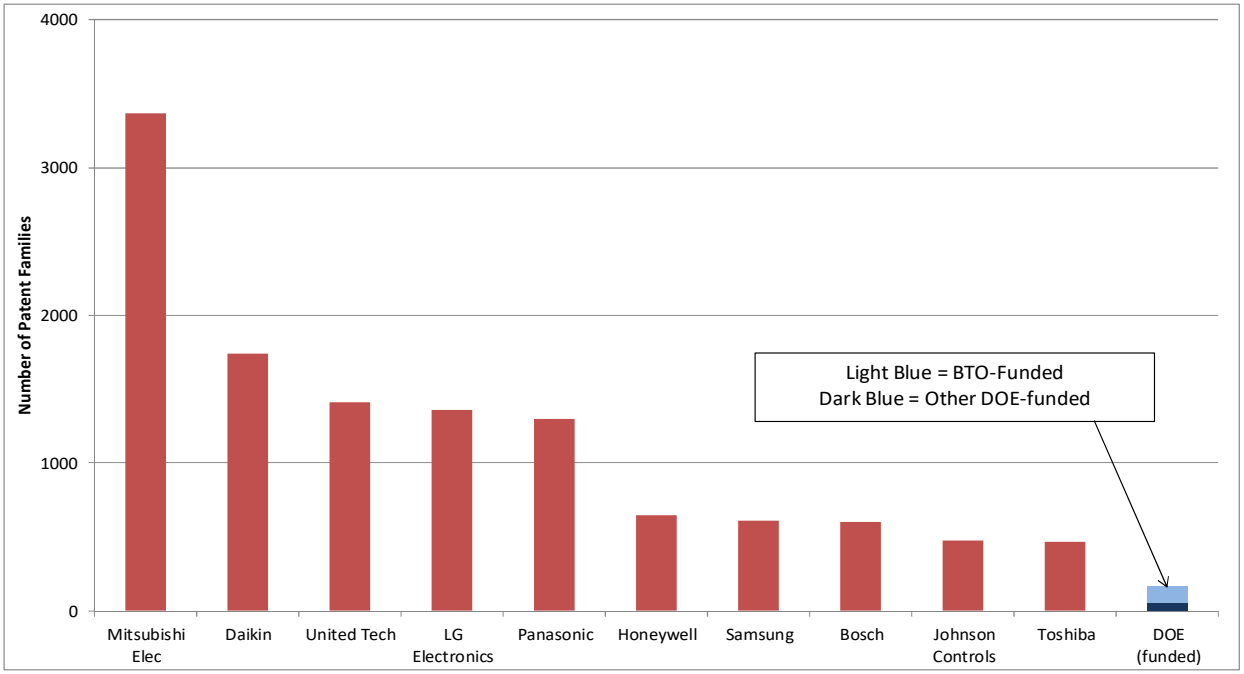


Figure 4-6 reveals that the Mitsubishi Electric has the largest HVAC patent portfolio, containing 3,367 patent families. This is almost twice as many patent families as the second-place company in Figure 4-6 – Daikin with 1,744 families. Daikin is then followed by United Technologies (1,411 families), LG Electronics (1,361 families) and Panasonic (1,297 families). One notable feature of Figure 4-6 is the geographical distribution of the leading companies, with six of the ten based in Asia, two in Europe (including Johnson Controls, now headquartered in Ireland) and two in North America. This reinforces the earlier point that, while the analysis does not include patents from Asian systems, this does not mean that patents associated with Asian companies are excluded.

The DOE-funded HVAC patent portfolio of 164 patent families (113 BTO-funded; 51 Other DOE-funded) is much smaller than the portfolios associated with the leading HVAC companies in Figure 4-6. In evaluating the influence of DOE-funded HVAC patents versus the influence of patents owned by the leading companies, we therefore take this difference in portfolio size into account. It should also be noted that there is a small amount of double-counting of patent families in this figure. Specifically, there are two patent families funded by BTO that are assigned to one of the leading companies (one each to Honeywell and Johnson Controls) plus one Other DOE-funded family assigned to United Technologies. These three patent families are counted in both the DOE-funded column in Figure 4-6 and in the respective company columns. This double-counting is appropriate, since these patent families are both funded by DOE and assigned to a leading company.

Assignees of BTO/Other DOE HVAC Patents

The DOE-funded HVAC patent portfolios are constructed somewhat differently from the portfolios of the leading companies listed in Figure 4-6. Specifically, DOE's 164 patent families are those funded by DOE, but they are not necessarily assigned to the agency. For example, BTO (or another DOE office) may have funded research projects at DOE labs or companies. In such cases, the assignees of any resulting patents may be the respective DOE lab managers or companies (such as the three leading company patent families referred to above).

Figure 4-7 shows the leading assignees on BTO-funded HVAC patent families. This chart is headed by DOE itself with 16 patent families. Patents may be assigned to DOE for various reasons, including where the inventors are federal employees; where the funding recipient elects not to pursue patent protection for, or take title to, the invention; or where the funding recipient does not have the right to take title to the invention. The second and third placed assignees are UT-Battelle and Lockheed Martin, both through their management of Oak Ridge National Laboratory (ORNL). Other DOE lab managers with BTO-funded patent families include MRIGlobal (National Renewable Energy Laboratory) and the University of California (Los Alamos National Laboratory and Lawrence Berkeley National Laboratory). Figure 4-7 also includes patent families assigned to companies, notably Phillips Engineering, Westinghouse, AIL Research and Consolidated Natural Gas Company.

Figure 4-7 - Assignees with Largest No. of BTO-Funded HVAC Patent Families

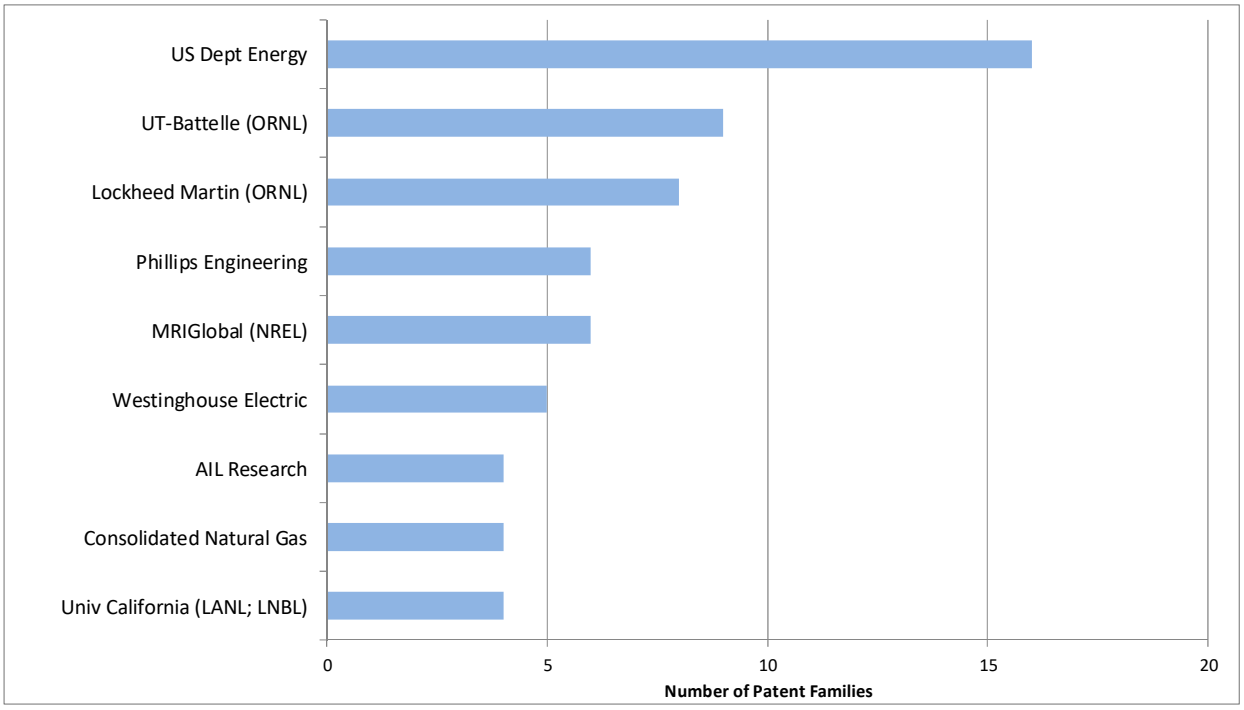


Figure 4-8 - Assignees with Largest No. of Other DOE-funded HVAC Patent Families

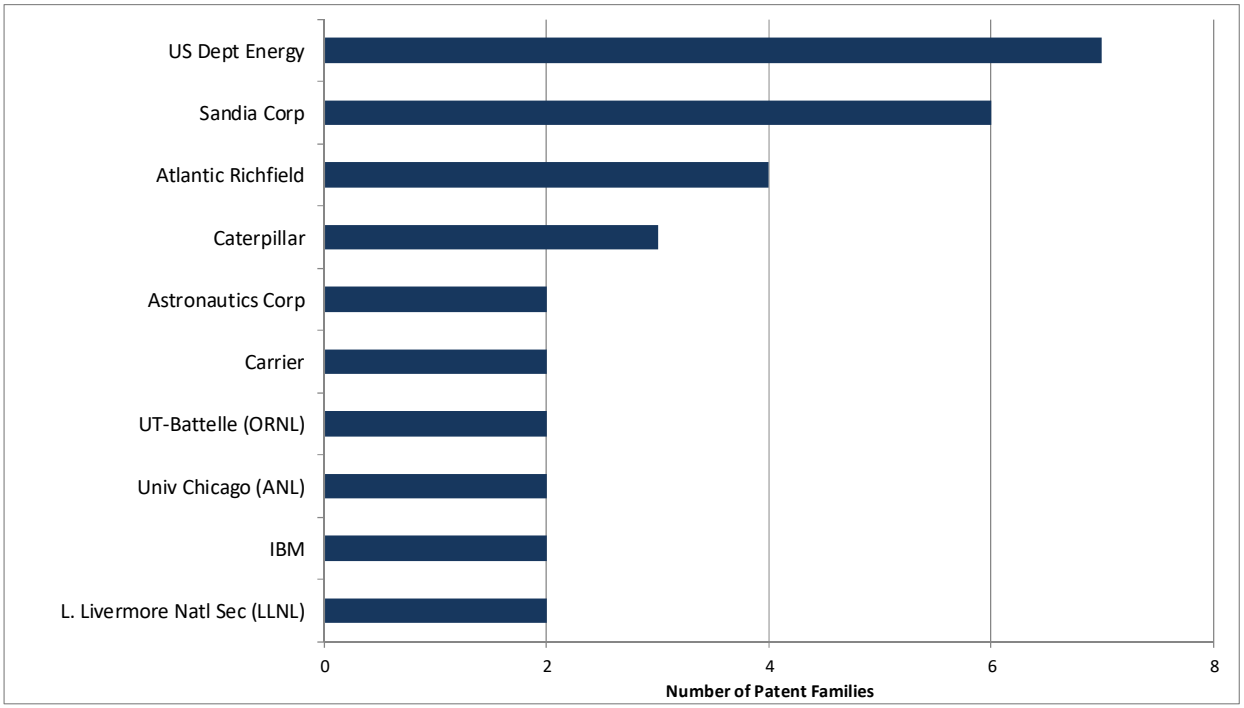


Figure 4-8 shows the leading assignees on Other DOE-funded HVAC patent families. There are only four assignees with more than two patent families in this figure. They are headed by DOE itself with seven patent families, followed by Sandia (six patent families), Atlantic Richfield

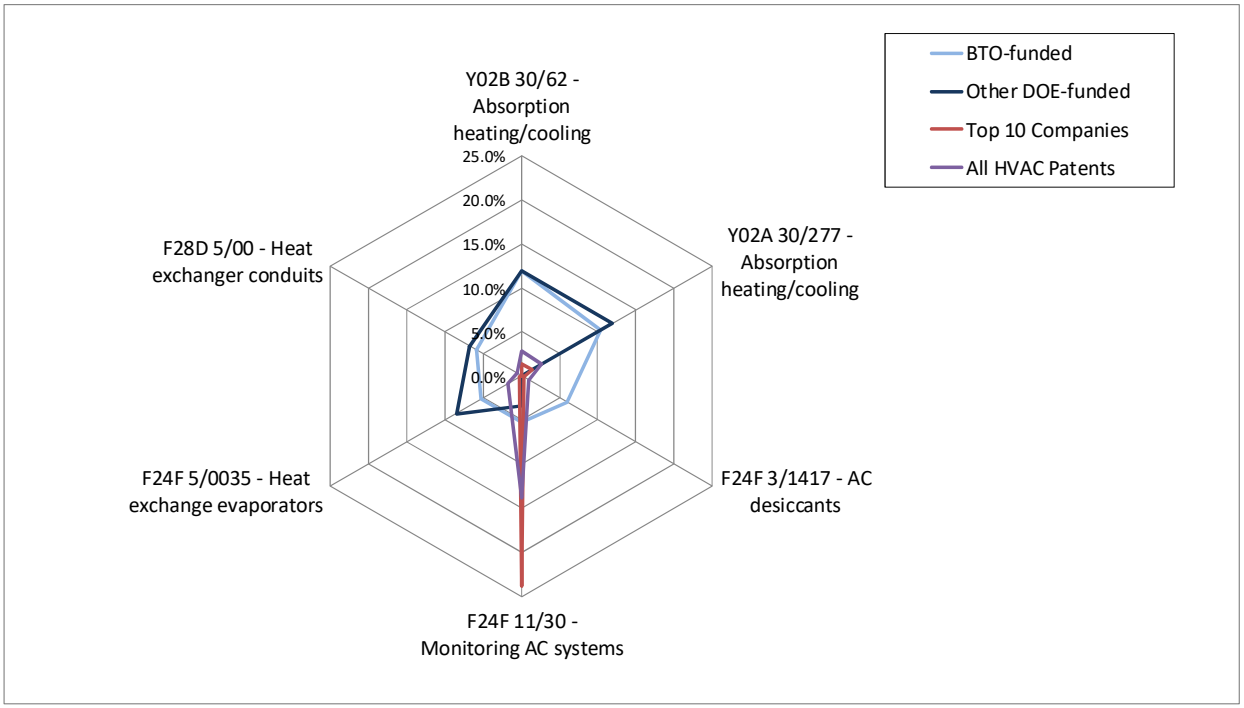
(four patent families) and Caterpillar (three patent families) The low numbers in Figure 4-8 are not surprising, given that there are only 51 Other DOE-funded HVAC patent families in total.

Distribution of HVAC Patents across Patent Classifications

We analyzed the distribution of BTO-funded HVAC U.S. patents across Cooperative Patent Classifications (CPCs).[9] We then compared this distribution to those associated with Other DOE-funded HVAC patents; HVAC patents assigned to the ten leading companies; and the universe of all HVAC patents. This analysis provides insights into the technological focus of BTO funding in HVAC, versus the focus of the remainder of DOE, leading HVAC companies, and HVAC technology in general.

The results from this CPC analysis are shown in two separate charts, each from a different perspective. The first chart (Figure 4-9) is based on the six CPCs that are most prevalent among BTO-funded HVAC patents. The purpose of this figure is thus to show the main focus areas of BTO-funded HVAC research, and the extent to which these areas translate to other portfolios (Other DOE-funded; leading HVAC companies; all HVAC).

Figure 4-9 - Percentage of HVAC U.S. Patents in Most Common Cooperative Patent Classifications (Among BTO-Funded Patents)



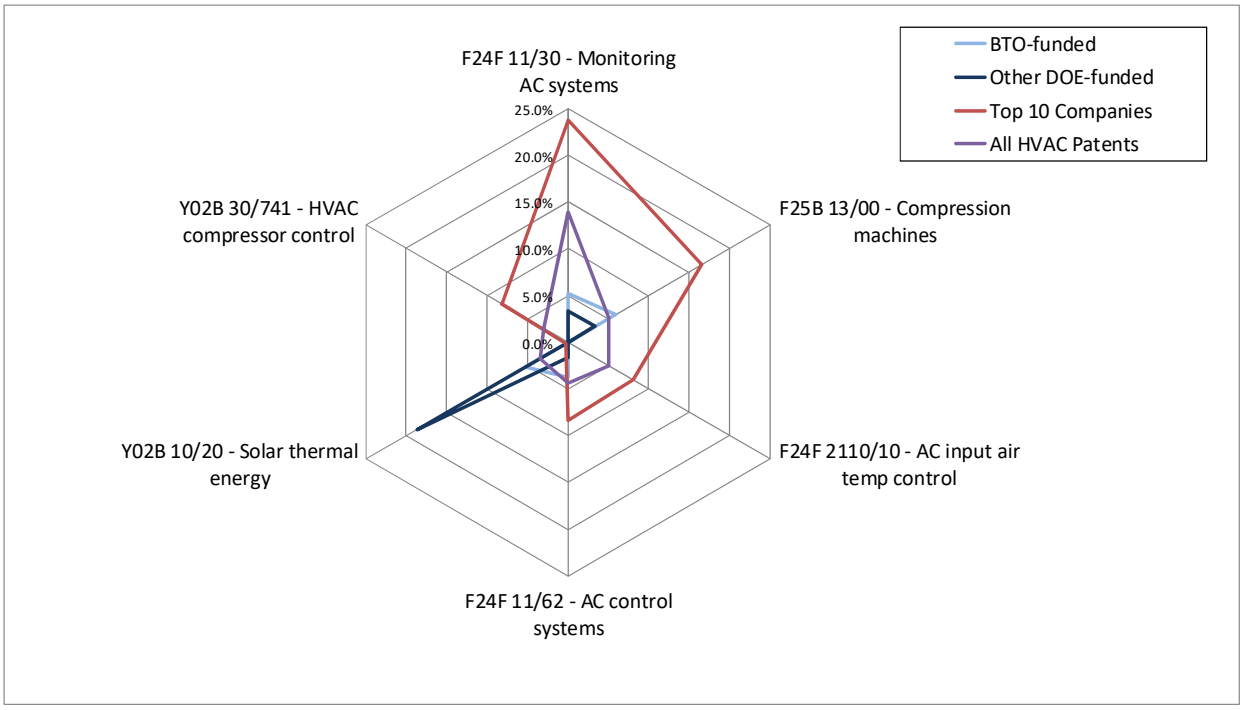
This figure shows that BTO-funded research includes relatively balanced coverage across the six CPCs (which is not particularly surprising, since the BTO-funded patent portfolio forms the basis for the CPCs included in the chart). The most common CPCs among BTO-funded patents relate

[9] The CPC is a patent classification system. Patent offices attach numerous CPC classifications to a patent, covering the different aspects of the subject matter in the claimed invention. In generating these charts, all CPCs associated with each patent are included.

to absorption heating and cooling (CPC Y02B 30/62 and Y02A 30/277), with over 10% of these patents having these CPCs attached. Other CPCs in this figure are concerned with heat exchanger components (CPC F03D 5/00 and F24F 5/0035) and desiccants for air conditioning systems (F24F 3/1417). The Other DOE-funded HVAC patents have a similar distribution across CPCs to the BTO-funded patents, but the same cannot be said for the portfolios of all HVAC patents, and HVAC patents owned by the leading companies. These two portfolios have a notable presence in only one out of the six CPCs in Figure 4-9 (F24F 11/30 – monitoring AC systems). This suggests that BTO-funded (and Other DOE-funded) HVAC patents have had a different focus to those owned by the leading companies. In the period 1976-2018, BTO funding may thus have helped fill a research gap not addressed extensively by leading HVAC companies.

Figure 4-10 is similar to Figure 4-9, except that it is from the perspective of the most common CPCs among all HVAC patents. Hence, the purpose of this chart is to show the main research areas within HVAC as a whole, and how these areas are represented in selected HVAC portfolios (BTO-funded; Other DOE-funded; leading HVAC companies).

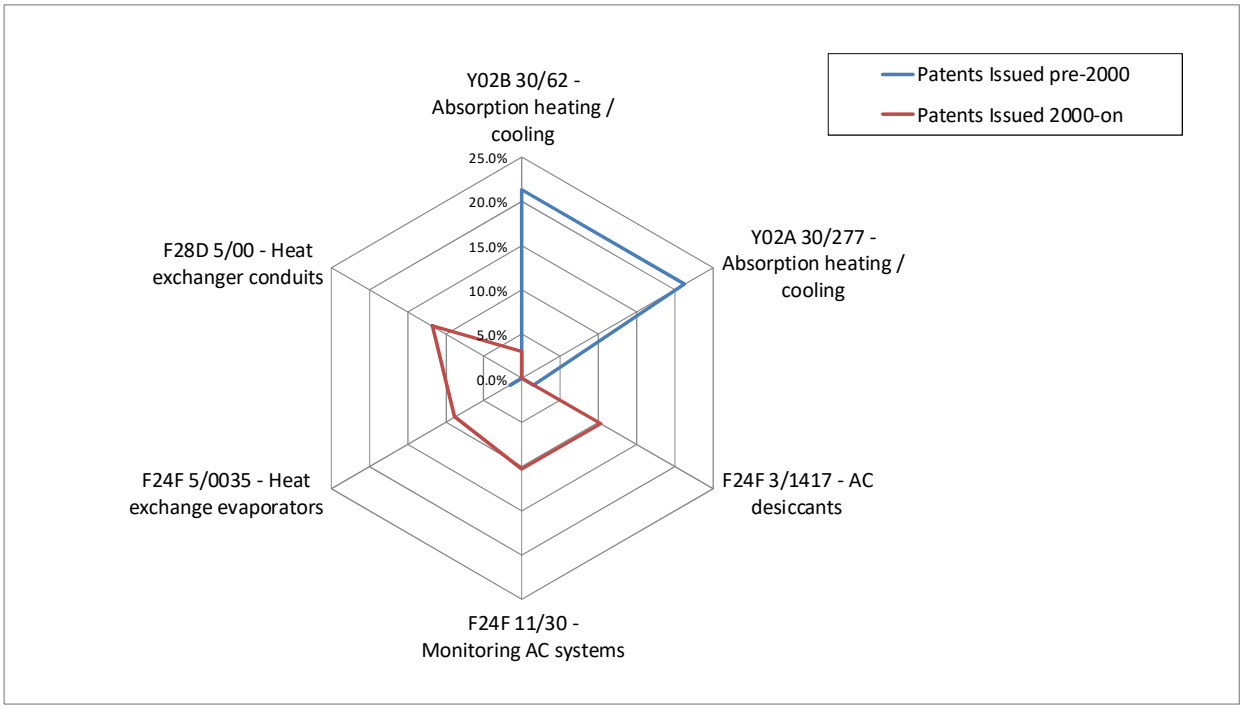
Figure 4-10 - Percentage of HVAC U.S. Patents in Most Common Cooperative Patent Classifications (Among All HVAC Patents)



Only one CPC in Figure 4-9 also appears in Figure 4-10 (F24F 11/30 – monitoring AC systems). The new CPCs in Figure 4-10 reflect a greater focus on compressors (CPC F25B 13/00 and Y02B 30/741), plus air conditioning control systems (CPC F24F 11/62 and F24F 2110/10). There is also a CPC for solar thermal energy (Y02B 10/20), in which Other DOE-funded patents have a notable presence (although the number of patents in this portfolio is relatively small). BTO-funded patents do not have a major presence in these new CPCs in Figure 4-10, reinforcing the finding from Figure 4-9 that these patents have a different focus to HVAC patents in general.

Figure 4-11 compares the CPC distribution of BTO-funded HVAC U.S. patents across two time periods – patents issued before 2000, and those issued from 2000 onwards. This figure reveals that the focus of BTO-funded patents has shifted markedly over time. In the pre-2000 period, the major concentration was on absorption-based heating and cooling (CPC Y02B 30/62 and Y02A 30/277). This technology is almost entirely absent among patents issued from 2000 onwards, with these patents focusing more on heat exchangers (CPC F03D 5/00 and F24F 5/0035), desiccants for air conditioning systems (F24F 3/1417) and monitoring air conditioning systems (CPC F24F 11/30).

Figure 4-11 - Percentage of BTO-funded HVAC U.S. Patents in Most Common Cooperative Patent Classifications across Two Time Periods



Tracing Backwards from HVAC Patents Owned by Leading Companies

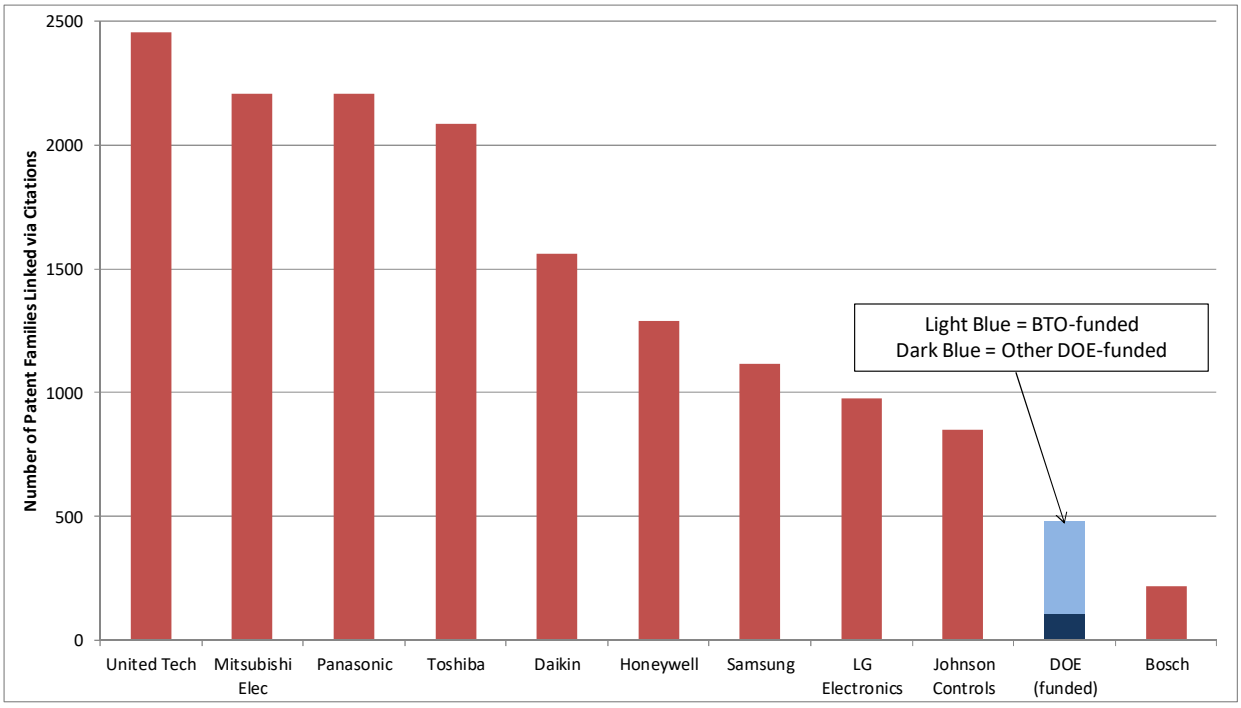
This section reports the results of an analysis tracing backwards from HVAC patents owned by leading companies in this technology to earlier research, including that funded by BTO (and by DOE in general). The results in this section are examined at two levels. First, we report results at the organizational level. These results reveal the extent to which BTO-funded (and Other DOE-funded) research forms a foundation for subsequent innovations associated with leading HVAC companies. Second, we drill down to the level of individual patents, with a particular focus on BTO-funded HVAC patents. These patent-level results highlight specific BTO-funded patents that have had a particularly strong influence on subsequent patents owned by leading companies. They also highlight which HVAC patents owned by these leading companies are linked particularly extensively to earlier BTO-funded research.

Organizational Level Results

In the organizational level results, we first compare the influence of BTO-funded and Other DOE-funded HVAC research against the influence of leading companies in this technology. We then look at which of these leading companies build particularly extensively on DOE-funded HVAC research.

Figure 4-12 compares the influence of BTO-funded and Other DOE-funded HVAC research to the influence of research carried out by the ten leading HVAC companies. Specifically, this figure shows the number of HVAC patent families owned by the leading companies that are linked via citations to earlier HVAC patent families assigned to each of these leading companies (plus patent families funded by DOE). In other words, this figure shows the companies whose patents have had the strongest influence upon subsequent developments made by leading companies in HVAC technology.[10]

Figure 4-12 - Number of Leading Company HVAC Patent Families Linked via Citations to Earlier HVAC Patents from each Leading Company
e.g. 479 leading company families are linked to earlier BTO/Other DOE-funded families



[10] This figure compares the influence of patents *funded* by BTO/Other DOE against patents *owned* by (i.e. assigned to) organizations. Such a comparison is reasonable, since patents funded by organizations through their R&D budgets will be assigned to those organizations. Also, organizations cannot choose to reference the patents of a non-competitor (such as DOE) rather than the patents of a competitor in order to reduce the "credit" given to that competitor. Such an omission could lead to the invalidation of their patents. Note that, as in Figure 4-6, there is a small amount of double-counting in Figure 4-12, as some patent families assigned to the leading companies were funded by DOE. Also, in Figure 4-12 and Figures 4-14 – 4-16, leading company patent families linked to both BTO-funded and Other DOE-funded patents are allocated to the BTO-funded segment of the DOE column, in order to avoid double-counting these families.

United Technologies is at the head of Figure 4-12. In total, 2,457 leading company HVAC patent families (i.e. 20.5% of these 11,972 families) are linked via citations to earlier United Technologies patents. Mitsubishi Electric is in second place, with 2,208 leading company patent families linked to its patents, followed by Panasonic (2,207 families) and Toshiba (2,087 families). DOE-funded patents are second-last in Figure 4-12, with a total of 479 leading company patent families linked to them (376 of which are linked to BTO-funded patents). At first glance, this does not appear promising in terms of DOE's influence in HVAC technology. However, Figure 4-12 does not take into account the different sizes of the patent portfolios associated with the various companies. For example, it is not surprising that many more patent families are linked via citations to Mitsubishi Electric than to DOE, since Mitsubishi has almost thirty times as many HVAC patent families available to be cited as prior art.

Figure 4-13 – Average Number of Leading Company HVAC Patent Families Linked via Citations to HVAC Families from Each Leading Company
e.g. on average, each DOE-funded patent family is linked to just under three subsequent patent families assigned to leading companies

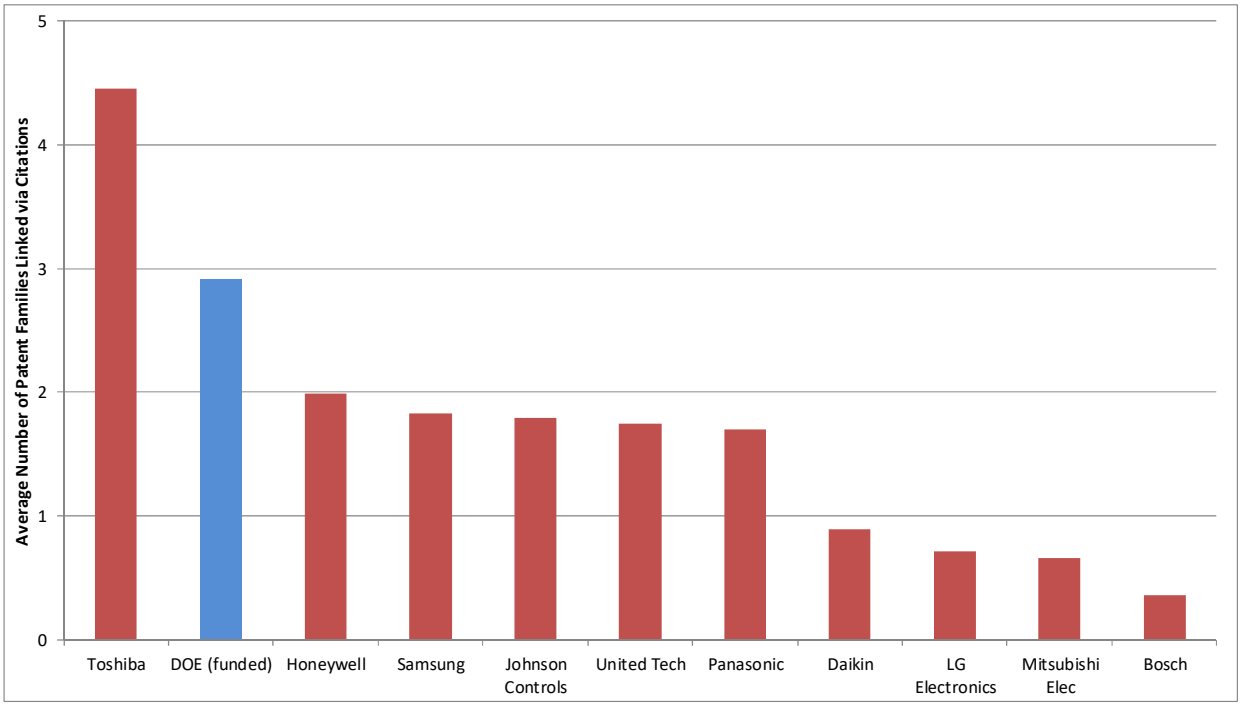


Figure 4-13 takes into account the differences in patent portfolio size. It shows the average (mean) number of leading company patent families linked to patent families associated with each of the leading companies, plus DOE. For example, on average, DOE-funded HVAC patent families (the majority of which are BTO-funded) are each linked to just under three patent families assigned to the leading companies. This puts DOE in second place in Figure 4-13, behind only Toshiba, whose patent families are linked to an average of 4.5 leading company families each. It means that, on average, more HVAC patent families owned by leading companies are linked via citations to each DOE-funded HVAC patent family than are linked to the HVAC patent families assigned to any other leading company (except Toshiba). Figure 4-13 thus suggests that, taking into account its relatively small size, the portfolio of DOE-funded

HVAC patents has had a notable influence on HVAC innovations associated with the leading companies.

Figures 4-14 through 4-16 examine which of the leading companies build particularly extensively on earlier BTO-funded and Other DOE-funded HVAC patents. Figure 4-14 shows how many HVAC patent families owned by each of the leading companies are linked via citations to at least one earlier DOE-funded HVAC patent. United Technologies is at the head of this figure, with 104 HVAC patent families linked via citations to earlier DOE-funded patents, 78 of which are linked to BTO-funded patents. Honeywell is second in Figure 4-14, with 87 patent families linked to DOE-funded patents (75 linked to BTO-funded patents), followed by LG Electronics (73 families linked to DOE; 57 to BTO), Mitsubishi Electric (54 linked to DOE; 45 to BTO) and Johnson Controls (43 linked to DOE; 37 to BTO).

Figure 4-14 - Number of Patent Families Assigned to Leading HVAC Companies Linked via Citations to Earlier BTO/Other DOE-funded HVAC Patents

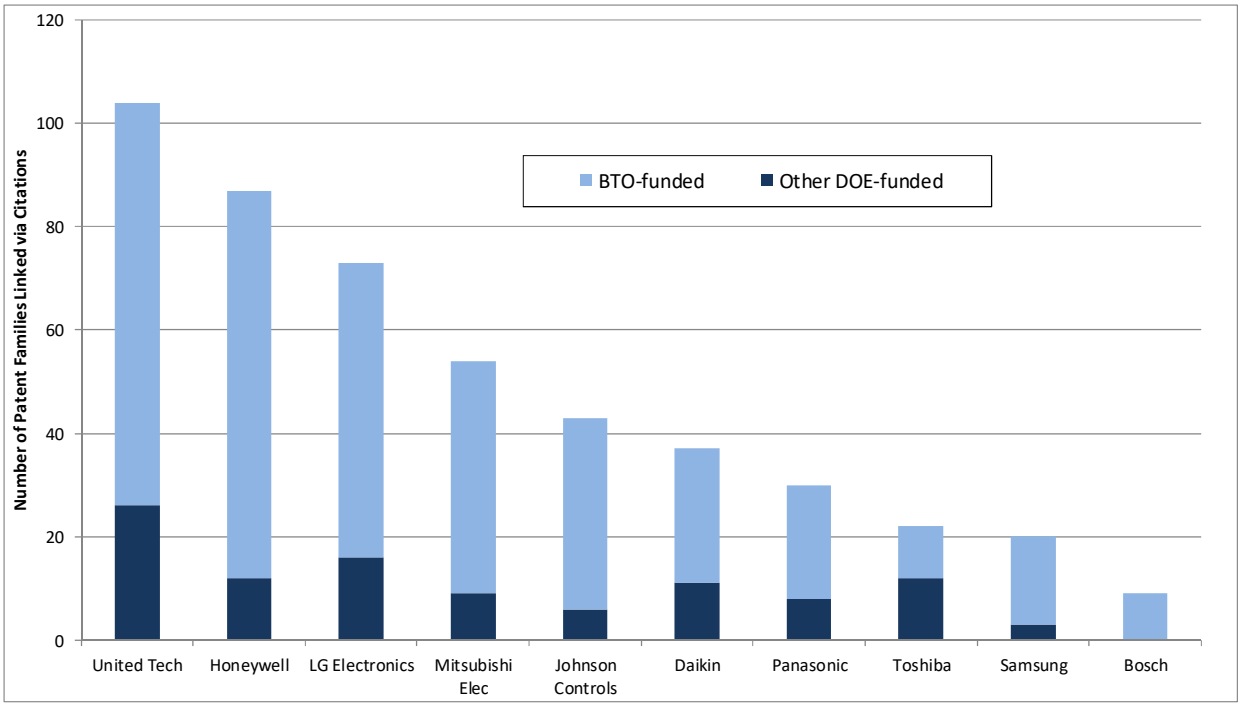


Figure 4-15 counts the total number of citation links from leading companies to earlier DOE-funded patents. This differs slightly from the count of linked families in Figure 4-14, since a single patent family may be linked to multiple earlier DOE-funded patents. In general, Figure 4-15 follows a similar pattern to Figure 4- 14. United Technologies is again at the head of Figure 4-15, with a total of 150 citation links to DOE-funded patents, 114 of which are links to BTO-funded patents. The biggest difference in Figure 4-15 versus Figure 4-14 is that Johnson Controls (84 citation links to DOE; 78 to BTO) moves ahead of Mitsubishi Electric (67 citation linked to DOE; 58 to BTO).

Figure 4-15 - Total Number of Citation Links from Leading HVAC Company Patent Families to Earlier BTO/Other DOE-funded HVAC Patents

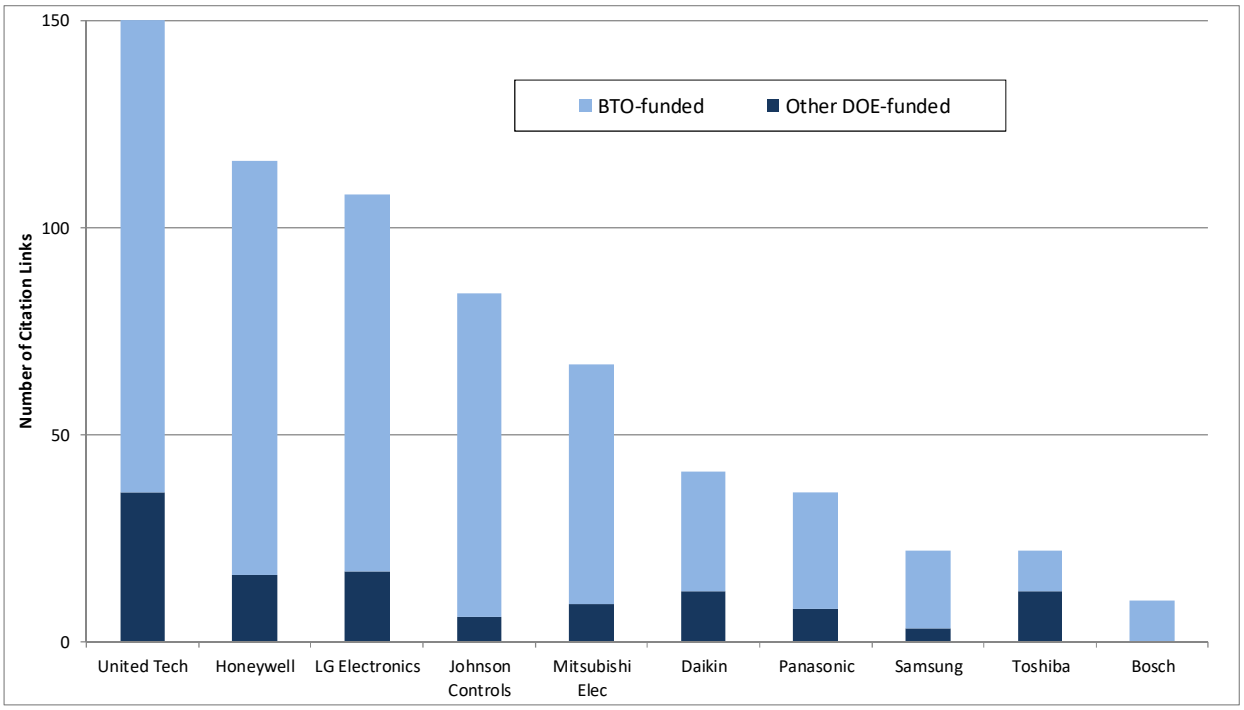
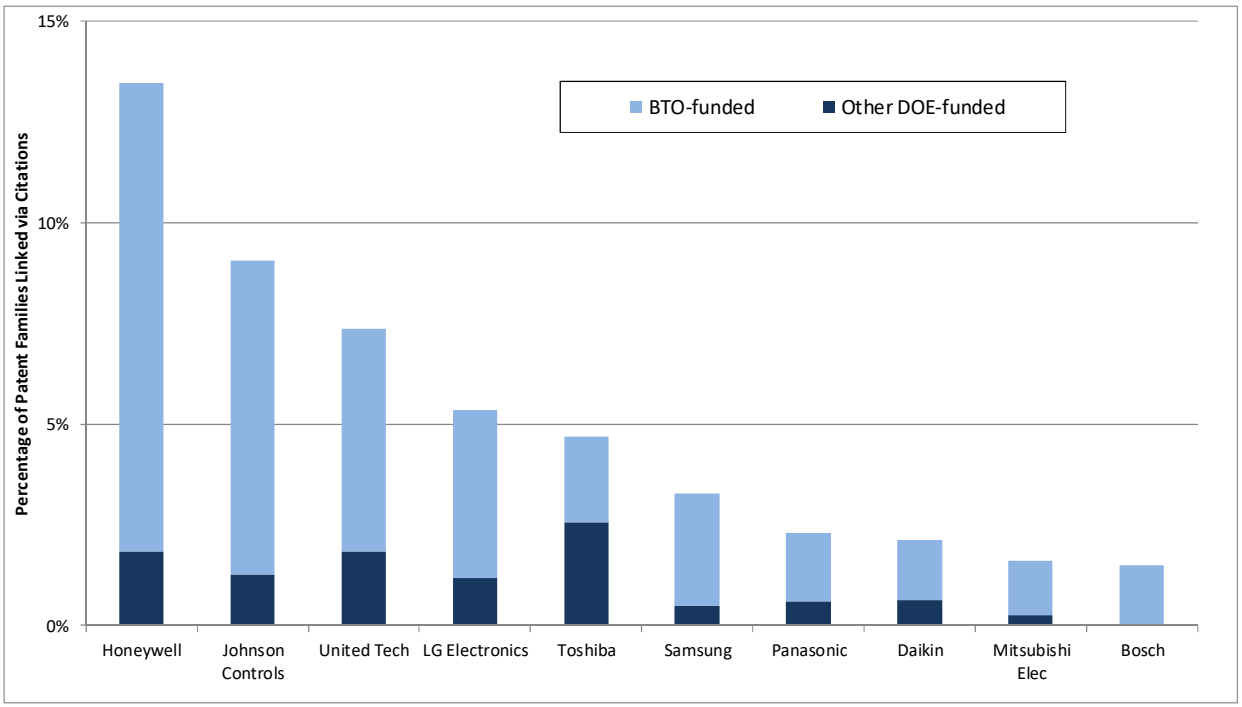


Figure 4-16 - Percentage of Leading HVAC Company Patent Families Linked via Citations to Earlier BTO/Other DOE-funded HVAC Patents



There is an element of portfolio size bias in the patent family counts in Figures 4-14 and 4-15. Companies with larger HVAC patent portfolios are likely to have more patent families linked to

DOE, simply because they have more families overall. Figure 4-16 accounts for this portfolio size bias by calculating the percentage of each leading company's HVAC patent families that are linked via citations to earlier DOE-funded HVAC patents, rather than their absolute number. This is a measure of how extensively each company builds on DOE-funded research, relative to their overall patent output.

Figure 4-16 is headed by Honeywell, with 13.5% of its HVAC patent families linked via citations to earlier DOE-funded HVAC patents (11.6% linked to BTO-funded HVAC patents). Johnson Controls is in second place in Figure 4-16 (9.1% of families linked via citations to DOE; 7.8% to BTO), followed by United Technologies (7.4% linked to DOE; 5.5% to BTO) and LG Electronics (5.4% linked to DOE; 4.2% to BTO). Mitsubishi Electric is less prominent in Figure 4-16, showing that its higher position in Figures 4-14 and 4-15 resulted largely from the size of its HVAC patent portfolio.

Patent Level Results

The previous section of the report examined results at the level of entire patent portfolios. The purpose of this section is to drill down to identify individual DOE-funded HVAC patent families (in particular BTO-funded families) that have had a particularly strong influence on subsequent HVAC patents owned by leading companies in this technology. Looking in the opposite direction, it also identifies individual HVAC patents owned by leading companies that have extensive links to earlier BTO-funded research.

Table 4-1 shows the BTO-funded HVAC patent families linked via citations to the largest number of subsequent patent families owned by leading companies in this technology.

Table 4-1 – BTO-Funded HVAC Patent Families Linked via Citations to Most Subsequent Leading Company HVAC Patent Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
24881021	6711470	2000	69	Bechtel BWXT Idaho (INL)	Method, system and apparatus for monitoring and adjusting the quality of indoor air
21800925	6778945	2001	47	Battelle Mem Inst (PNNL)	Rooftop package unit diagnostician
21937614	4217765	1979	26	Atlantic Richfield	Heat exchanger accumulator
25464707	4732008	1986	25	US Dept Energy	Triple effect absorption chiller utilizing two refrigeration circuits
23858044	4449376	1983	21	Westinghouse Electric	Indoor unit for electric heat pump
23469401	5628200	1995	17	Wallace Heating & AC	Heat pump system with selective space cooling
23833962	4470271	1983	17	Westinghouse Electric	Outdoor unit construction for an electric heat pump
22989132	4921515	1988	16	Univ California (LBNL)	Advanced regenerative absorption refrigeration cycles
25386677	5245833	1992	16	Lockheed Martin (ORNL)	Liquid overfeeding air conditioning system and method
26793952	5845502	1996	15	Lockheed Martin (ORNL)	Heat pump having improved defrost system

Two BTO-funded patent families stand out in Table 4-1, in terms of the number of leading company patent families linked to them via citations. The patent family at the head of this table (whose representative patent[11] is US #6,711,470) was filed in 2000 and assigned to Bechtel BWXT Idaho, through its former management of Idaho National Laboratory (INL). It describes a method for monitoring indoor air environments, and making adjustments to HVAC systems in cases of poor air quality. This INL family is linked via citations to 69 patent families assigned to the ten leading companies, including families assigned to seven of these ten companies (all except Bosch, Panasonic and Toshiba). The second-place patent family in Table 4-1 (representative patent US #6,778,945) is assigned to Battelle Memorial Institute, through its management of Pacific Northwest National Laboratory (PNNL). This patent family was filed in 2001, and describes a method for remote monitoring of HVAC system performance. It is linked to 47 patent families owned by the leading companies, including families from the same seven companies that are linked to the INL patent family at the head of Table 4-1.

Table 4-1 lists BTO-funded patents linked to the most subsequent HVAC patent families owned by leading companies. Table 4-2 looks in the opposite direction, and lists HVAC patent families owned by leading companies that are linked via citations to multiple BTO families.

Table 4-2 - Leading Company HVAC Patent Families Linked via Citations to Largest Number of BTO-Funded HVAC Patent Families

Patent Family #	Representative Patent #	Priority Year	# BTO Families	Assignee	Title
19454035	5916258	1996	9	LG Electronics	GAX aqua absorption type heat pump
19462540	5857355	1996	7	LG Electronics	Ammonia generator absorber heat exchanger cycle
51390150	9518765	2013	5	Mitsubishi Electric	System and method for controlling temperature and humidity in multiple spaces using liquid desiccant
55969496	9964328	2016	5	Johnson Controls	User control device with cantilevered display
22876564	5584193	1994	5	Johnson Controls	Absorption-type refrigeration systems and methods
24104193	6250089	2000	5	United Technologies	Hot water condenser for multi-stage absorption system
21945018	5931007	1998	5	United Technologies	Absorption refrigeration system with condensate solution coupling
19144365	6748762	2001	4	Panasonic	Absorption-refrigerator
49160344	9644876	2012	4	Mitsubishi Electric	Refrigeration cycle apparatus

This table is headed by two LG Electronics patent families. These two patent families (representative patent US #5,916,258 and US #5,857,355) were both filed in 1996 and describe generator absorber heat exchangers (GAX). They are linked via citations to nine and seven earlier BTO-funded patent families respectively, notably patent families from the early 1980s assigned to DOE describing absorption refrigeration systems. Table 4-2 also includes a number of more recent patent families. For example, Mitsubishi Electric has a 2013 patent family (representative patent US 9,518,765) describing a liquid desiccant-based air conditioning system. This Mitsubishi family is linked via citations to five earlier BTO-funded HVAC patent families,

[11] The representative patent is a single patent from a family, but it is not necessarily the priority filing.

notably AIL Research families outlining heat exchangers. Johnson Controls has a 2016 patent family in Table 4-2 that is also linked to five earlier BTO-funded HVAC patent families. This Johnson Controls family (representative patent US #9,964,328) outlines an HVAC thermostat with a cantilevered display panel. Among the BTO-funded patent families to which it is linked are the INL and PNNL patent families at the head of Table 4-1.

We also identified high-impact HVAC patents owned by leading companies that have citation links back to BTO-funded patents.[12] The idea is to highlight important technologies owned by leading companies that are linked to earlier HVAC research funded by BTO. Table 4-3 lists leading company patents that are linked via citations to earlier BTO-funded patents, and in turn have been cited as prior art by at least 40 subsequent patents, resulting in a Citation Index value above two (i.e. they have each been cited at least twice as many times as expected given their age and technology).

Table 4-3 - Highly Cited Leading Company HVAC Patents Linked to Earlier BTO-funded HVAC Patents

US Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
9033255	2015	45	16.10	Honeywell	Wireless controller with gateway
8902071	2014	23	6.65	Honeywell	HVAC controller with HVAC system fault detection
6925823	2005	75	6.64	United Technologies	Refrigerant cycle with operating range extension
6560968	2003	56	3.81	LG Electronics	Thermoelectric cooler
6182461	2001	51	3.23	United Technologies	Photocatalytic oxidation enhanced evaporator coil surface for fly-by control
6019677	2000	35	2.88	Johnson Controls	Modular integrated terminals and associated systems for heating and cooling
6448896	2002	114	2.68	United Technologies	Air filter monitor for HVAC units
8560127	2013	22	2.37	Honeywell	HVAC control with comfort/economy management
6055814	2000	57	2.24	Samsung	Method of and apparatus for cooling an operating system using the Peltier effect
5503222	1996	47	2.06	Honeywell	Carousel heat exchanger for sorption cooling process

[12] High-impact patents are identified using 1790's Citation Index metric. This metric is derived by first counting the number of times a patent is cited as prior art by subsequent patents. This number is then divided by the mean number of citations received by peer patents from the same issue year and technology (as defined by their first listed Cooperative Patent Classification). For example, the number of citations received by a 2010 patent in CPC F24F 11/30 (Monitoring AC Systems) is divided by the mean number of citations received by all patents in that CPC issued in 2010. The expected Citation Index for an individual patent is one. The extent to which a patent's Citation Index is greater or less than one reveals whether it has been cited more or less frequently than expected, and by how much. For example, a Citation Index of 1.5 shows that a patent has been cited 50% more frequently than expected. Meanwhile a Citation Index of 0.7 reveals that a patent has been cited 30% less frequently than expected. By extension, the expected Citation Index for a portfolio of patents is also one, with values above one showing that a portfolio has been cited more than expected, and values below one showing that a portfolio has not been cited as frequently as expected. Note that the Citation Index is calculated for U.S. patents only, due to the differences in citation practices across different countries' patent systems.

Honeywell features prominently in Table 4-3, and is responsible for the two patents at the head of the table. The first of these patents (US #9,033,255) describes a thermostat that can be controlled remotely via wireless communications. It has been cited as prior art by 45 subsequent patents, sixteen times as many citations as expected for a patent of its age and technology. The second Honeywell patent in Table 4-3 (US #8,902,071) outlines a system for monitoring HVAC system performance. It has been cited as prior art by 23 subsequent patents, more than six times as many citations as expected. In terms of raw citation counts, United Technologies has the two highest-cited patents in Table 4-3. The first of these (US #6,925,823) describes a method for controlling HVAC compressors to prevent overload, and has been cited by 75 subsequent patents (six times as many as expected). The second United Technologies patent (US #6,448,896) was issued in 2002 has been cited by 114 subsequent patents (more than twice as many as expected). It describes an air filter monitor for air conditioning units

While the patent-level results focus on BTO-funded HVAC patent families, we also identified Other DOE-funded HVAC families linked to the largest number of subsequent patent families owned by leading companies in this technology. These Other DOE-funded families are listed in Table 4-4. Two patent families stand out in this table, in terms of the number of leading company patent families linked to them. Both are from the earliest years in the analysis, are assigned to Atlantic Richfield, and describe heat pumps. The first of these Atlantic Richfield patent families (representative patent US #4,336,692) is linked via citations to 32 subsequent patent families assigned to eight of the ten leading companies (all except Bosch and Samsung), with a number of these families being relatively recent. The second Atlantic Richfield patent family (representative patent US #4,380,156) is linked to 23 subsequent patent families assigned to six of the ten leading companies, again including a number of recent families.

Table 4-4 - Other DOE-Funded HVAC Patent Families Linked via Citations to Most Subsequent Leading Company HVAC Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
22492449	4336692	1980	32	Atlantic Richfield	Dual source heat pump
27366683	4380156	1979	23	Atlantic Richfield	Multiple source heat pump
22492447	4308042	1980	9	Atlantic Richfield	Heat pump with freeze up prevention
22800489	4372376	1980	9	US Dept Energy	Heat pump apparatus
22214054	5462610	1993	8	Iowa State Univ	Lanthanide Al-Ni base Ericsson cycle magnetic refrigerants
25373255	4176523	1978	6	Garrett Corp	Adsorption air conditioner
22534323	4313424	1980	5	US Dept Energy	Solar heating system
23743315	6230503	1999	5	Sandia Corp	Method and apparatus for extracting water from air
46204872	6880344	2002	4	UTC Power	Combined rankine and vapor compression cycles
27031917	6511525	1999	3	Sandia Corp	Method and apparatus for extracting water from air using a desiccant

Overall, the backward tracing element of the analysis suggests that, taking into account their comparatively small size, the portfolios of BTO-funded and Other DOE-funded HVAC patents have had a notable influence on subsequent innovations associated with the leading HVAC companies. This influence can be seen both over time, and across these leading companies, with

a number of BTO-funded patent families linked via citations to subsequent patents assigned to many of the leading companies.

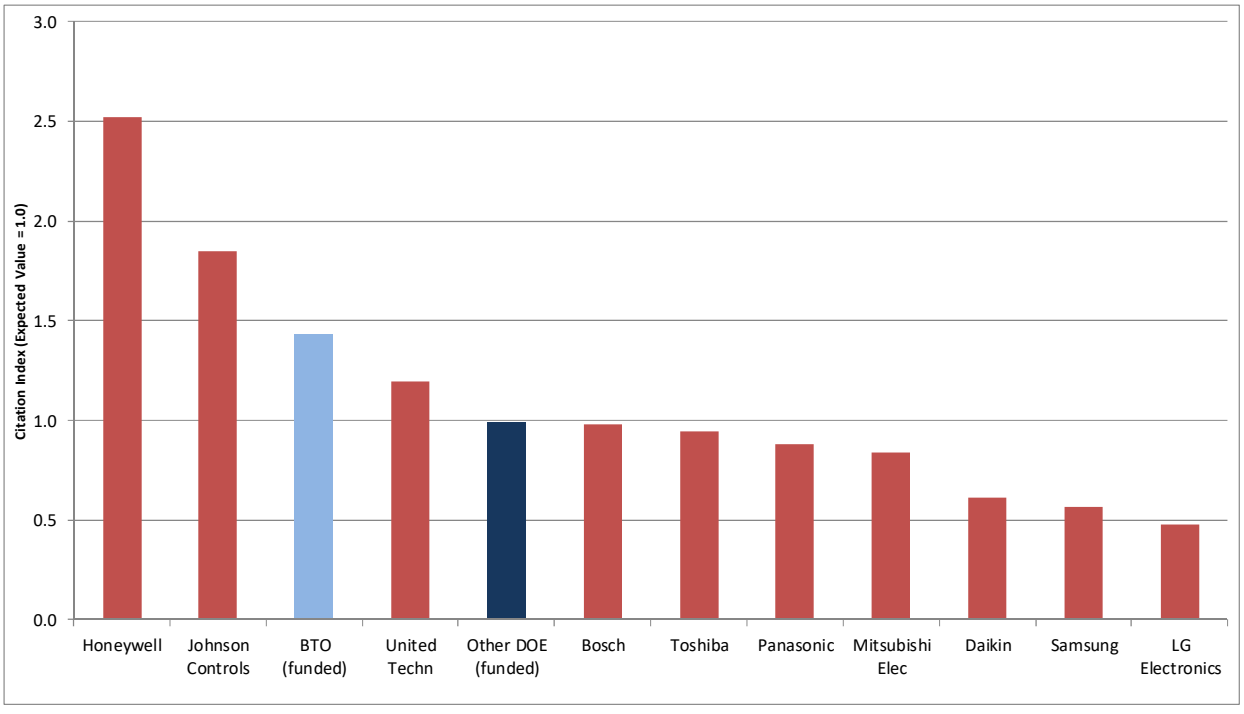
Tracing Forwards from DOE-funded HVAC Patents

The previous section of the report examines the influence of DOE-funded HVAC research upon technological developments associated with leading HVAC companies. That analysis was based on tracing backwards from the patents of leading companies to previous generations of research. This section reports the results of an analysis tracing in the opposite direction – starting with BTO-funded (and Other DOE-funded) HVAC patents, and tracing forwards in time through two generations of citations. Hence, while the previous section of the report focuses on DOE's influence upon a specific patent set (i.e. patents owned by leading HVAC companies), this section of the report focuses on the broader influence of BTO-funded (and Other DOE-funded) HVAC research, both within and beyond the HVAC industry. Also, in order to avoid repeating earlier results, the forward tracing concentrates primarily on patents that are linked to DOE-funded HVAC research, but are not owned by leading HVAC companies.

Organizational Level Results

We first generated Citation Index values for the portfolios of BTO-funded and Other DOE-funded HVAC patents. We then compared these Citation Indexes against those of the twelve leading HVAC companies. The results are shown in Figure 4-17.

Figure 4-17 - Citation Index for Leading Companies' HVAC Patents, plus BTO-funded and Other DOE-funded HVAC Patents

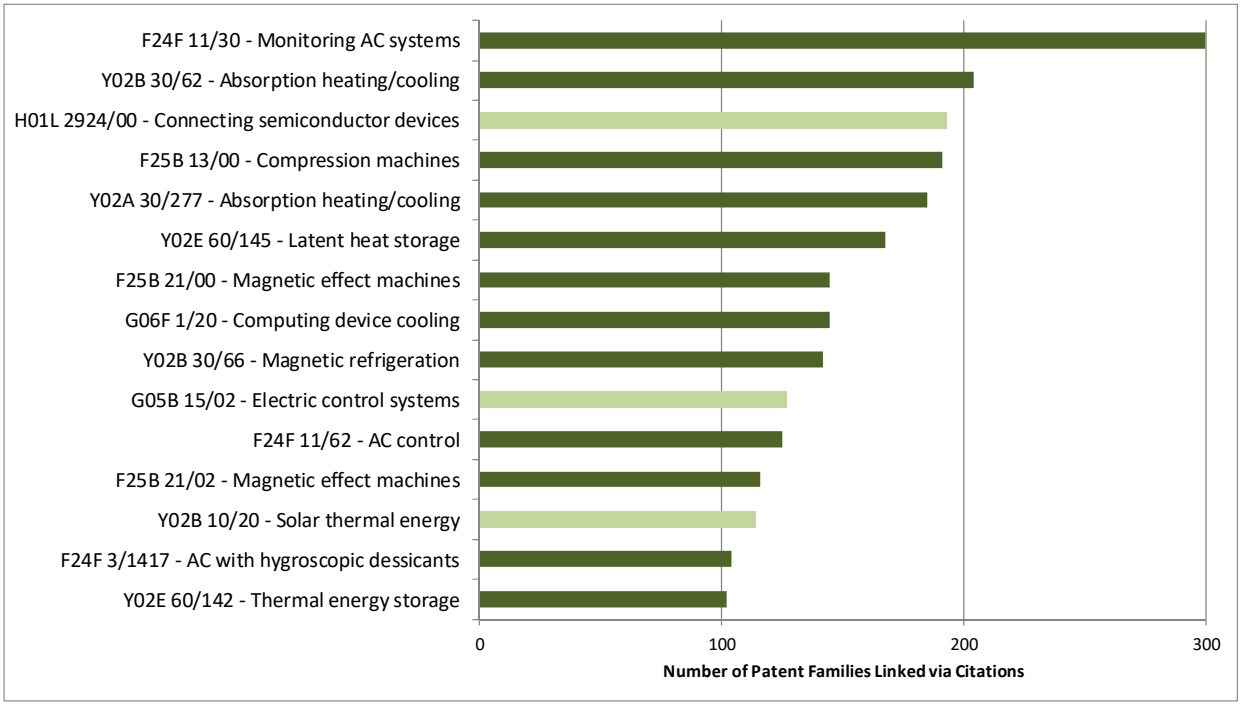


This figure reveals that BTO-funded HVAC patents have an average Citation Index of 1.43, showing they have been cited 43% more frequently than expected by subsequent patents. This places BTO-funded patents in third place in Figure 4-17, behind only Honeywell (Citation Index = 2.52) and Johnson Controls (Citation Index = 1.85). The Citation Index for Other DOE-funded HVAC patents is lower at 0.99, but this still means that these patents have been cited about as frequently as expected.

The Citation Index metric measures the overall influence of the DOE-funded HVAC patent portfolios, but does not necessarily address the breadth of this influence across technologies. We therefore identified the Cooperative Patent Classifications (CPCs) of the patent families linked via citations to earlier BTO-funded (and Other DOE-funded) HVAC patent families.[13] These CPCs reflect the influence of DOE-funded research across technologies.

Figure 4-18 shows the CPCs with the largest number of patent families linked to BTO-funded HVAC patents. The CPCs in this figure are shown in two different colors – i.e. dark green for CPCs related to HVAC technology and light green for CPCs beyond HVAC. All but three of the CPCs in Figure 4-18 are in technologies related to HVAC, with the most common CPCs being F24F 11/30 (Monitoring AC systems) and Y02B 30/62 (Absorption heating/cooling). The three CPCs beyond HVAC technology are H01L 2924/00 (Connecting semiconductor devices), G05B 15/02 (Electric control systems) and Y02B 10/20 (Solar thermal energy). These are examples of BTO-funded HVAC patents influencing developments in other technologies.

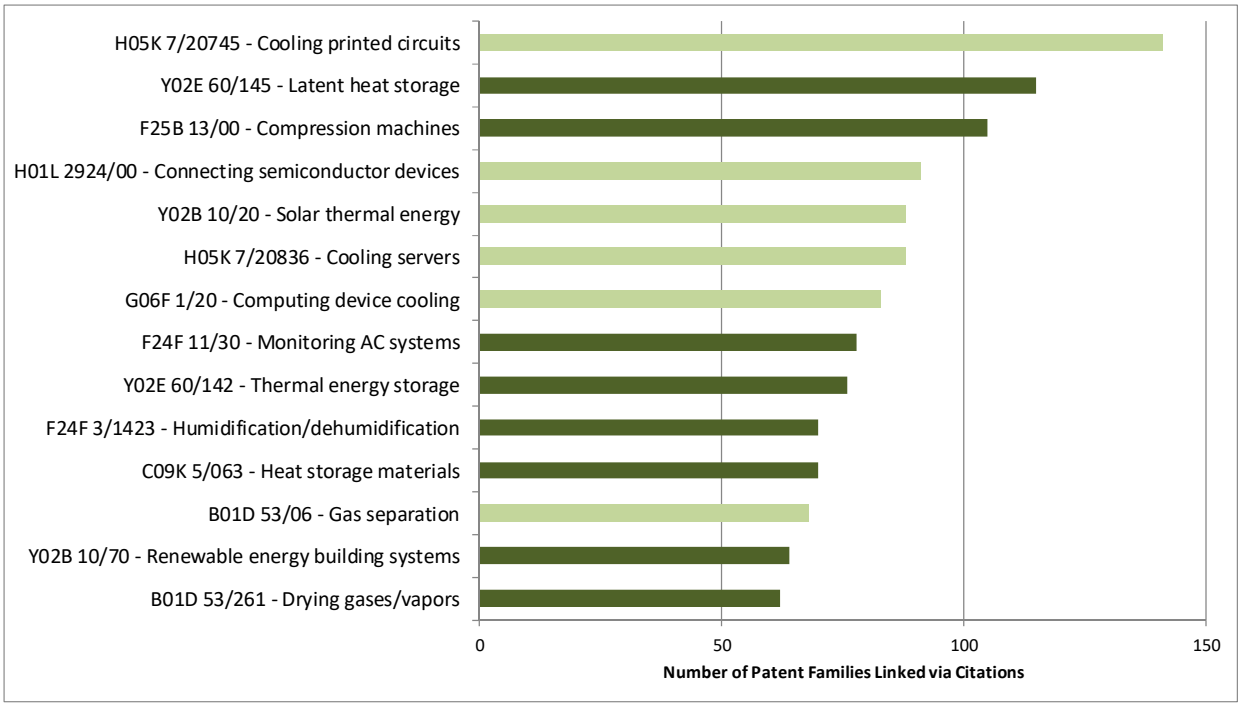
Figure 4-18 - Number of Patent Families Linked via Citations to Earlier BTO-Funded HVAC Patents by CPC (Dark Green = HVAC-related; Light Green = Other)



[13] Patents typically have numerous CPCs attached to them, reflecting different aspects of the invention they describe. In this analysis, we include all CPCs attached to the patents linked to earlier DOE-funded patent families.

Figure 4-19 is similar to Figure 4-18, but is based on patent families linked to Other DOE-funded HVAC patents. There is a much greater presence in this figure of CPCs from beyond HVAC technology. These include CPCs related to cooling printed circuits (H05K 7/20745), servers (H05K 7/20836) and computing devices (G06F 1/20), with the citation links in the first of these CPCs then extending into further links to technologies related to connecting semiconductor devices (CPC H01L 2924). Again, these are examples of Other DOE-funded HVAC research influencing developments in other technologies.

Figure 4-19 - Number of Patent Families Linked via Citations to Earlier Other DOE-Funded HVAC Patents by CPC (Dark Green = HVAC-related; Light Green = Other)



The organizations with the largest number of patent families linked via citations to earlier BTO-funded HVAC patents are shown in Figure 4-20. To avoid repeating the results from earlier, this figure excludes the ten leading HVAC companies used in the backward tracing element of the analysis. Also, note that Figure 4-20 includes all patent families assigned to these organizations, not just their patent families describing HVAC technology.

Figure 4-20 contains various very large companies with interests in many technologies. General Electric is at the head of this figure, with 211 patent families linked via citations to earlier BTO-funded HVAC patents. These General Electric patent families describe a range of technologies, including refrigeration, steam power plants and advanced materials. IBM is in second place in Figure 4-20 with 209 patent families linked via citations to earlier BTO-funded HVAC patents. These IBM patent families describe cooling technologies, especially for electronic devices and data centers. The remaining companies in Figure 4-20 are from a range of industries, including energy, healthcare and electronics.

Figure 4-20 - Organizations with Largest Number of Patent Families Linked via Citations to BTO-funded HVAC Patents (excluding leading HVAC companies)

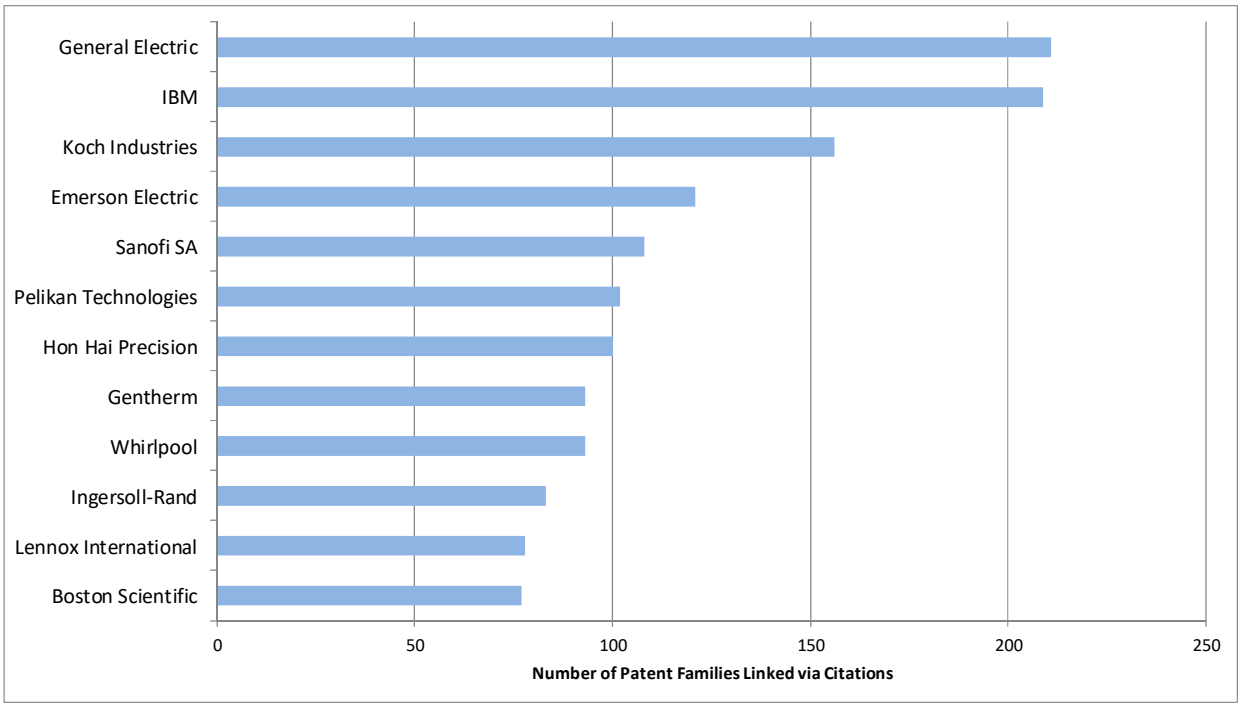


Figure 4-21 - Organizations with Largest Number of Patent Families Linked via Citations to Other DOE-funded HVAC Patents (excluding leading HVAC companies)

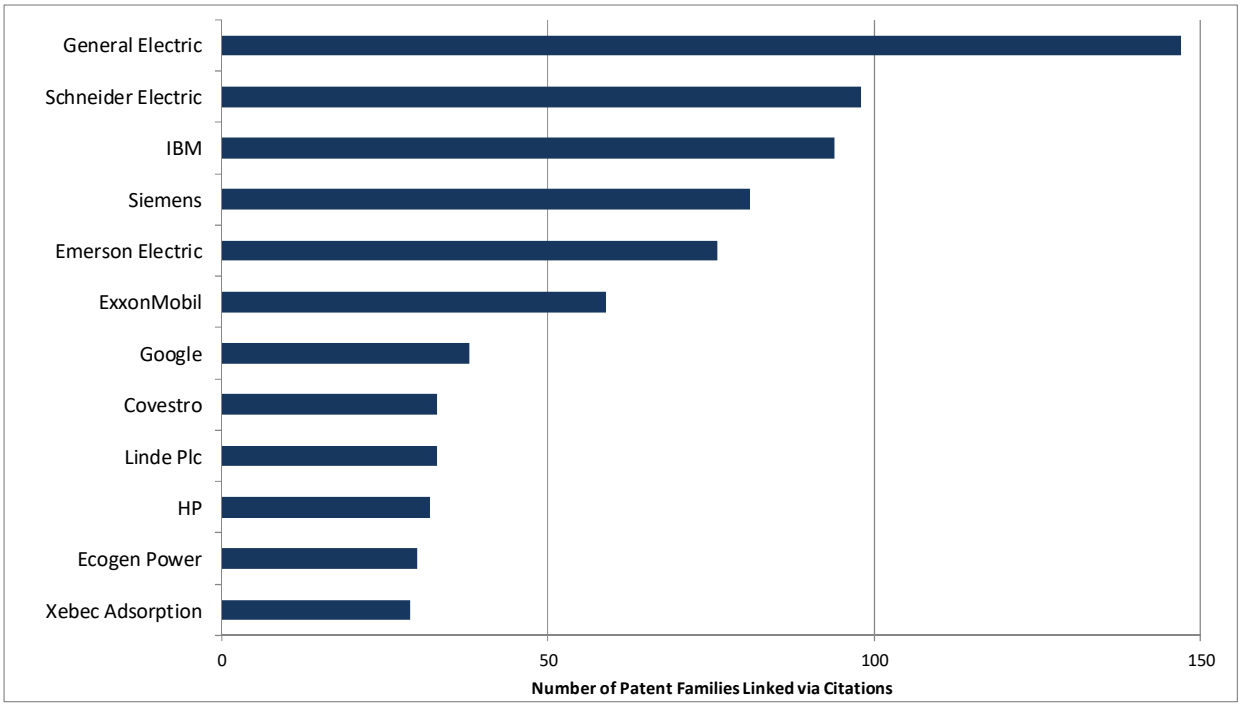


Figure 4-21 shows the organizations with the largest number of patent families linked via citations to earlier Other DOE-funded HVAC patents. This figure is again headed by General Electric, with 147 patent families linked via citations to Other DOE-funded HVAC patents,

including families describing cryogenic technology and household appliances. IBM is also prominent again, with 94 patent families linked to Other DOE-funded HVAC patents, many of them related to cooling electronic devices and data centers. Also prominent in Figure 4-21 are energy and manufacturing companies such as Schneider, Emerson and Siemens.

Patent Level Results

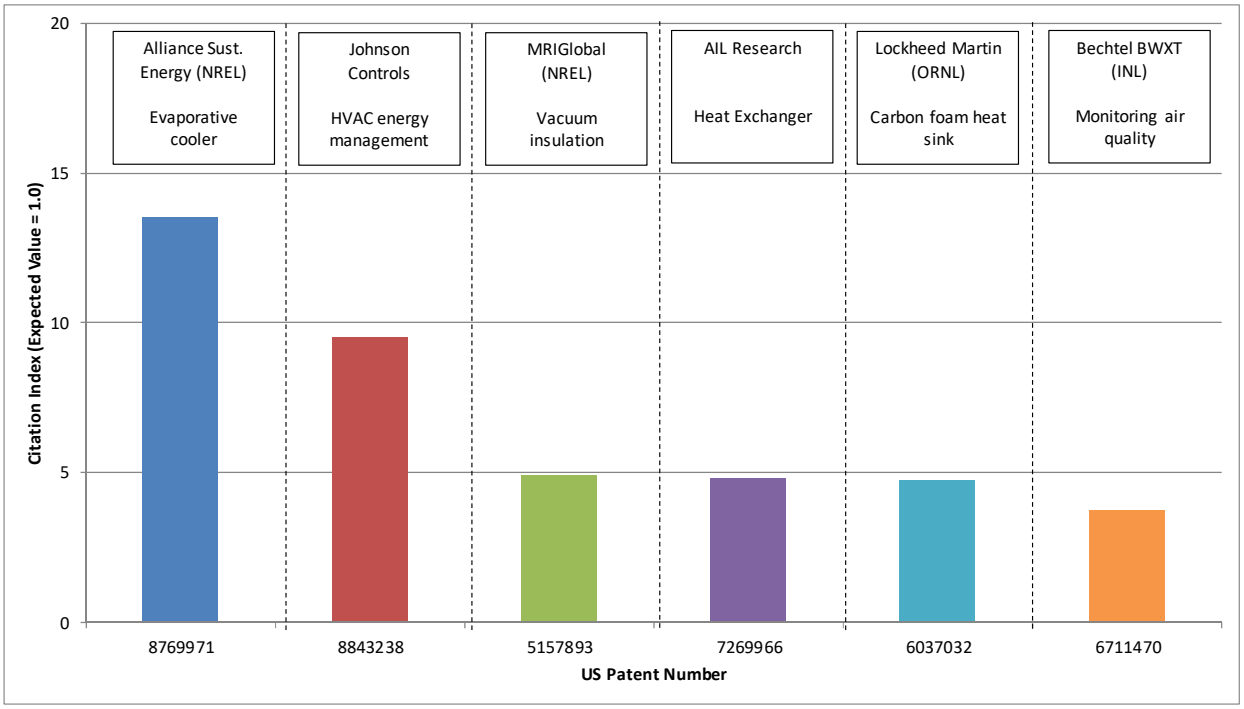
This section of the report drills down to identify individual DOE-funded (and particularly BTO-funded) HVAC patents whose influence on subsequent technological developments has been particularly strong. It also highlights patents that have extensive citation links to earlier BTO-funded HVAC research.

The simplest way of identifying high-impact BTO-funded HVAC patents is via overall Citation Indexes. The BTO-funded patents with the highest Citation Index values are shown in Table 4-5, with selected patents also presented in Figure 4-22. The patent at the head of this table (US #8,769,971) is assigned to the Alliance for Sustainable Energy, through its management of the National Renewable Energy Laboratory (NREL). This patent, which was issued in 2014, describes an evaporative cooler with a dehumidification capability. It has been cited as prior art by 37 subsequent patents, more than thirteen as many citations as expected given its age and technology. The patent in second place in Table 4-5 (US #8,843,238) was also issued in 2014. It is assigned to Johnson Controls, and outlines a system for controlling HVAC energy consumption in buildings. It has been cited by 33 subsequent patents, over nine times as many citations as expected. Table 4-5 contains two patents that have been cited as prior art by 100 or more subsequent patents. The first (US #6,711,470) is part of the Bechtel BWXT (INL) air quality patent family highlighted in the backward tracing element of the analysis (see Table 4-1). The second (US #5,157,893) is assigned to MRIGlobal (formerly Midwest Research Institute), through its management of NREL, and describes ultra-thin insulation panels.

Table 4-5 – List of Highly Cited BTO-Funded HVAC Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
8769971	2014	37	13.51	Alliance for Sustain. Energy (NREL)	Indirect evaporative cooler using membrane-contained, liquid desiccant for dehumidification
8843238	2014	33	9.54	Johnson Controls	Systems and methods for controlling energy use in a building management system using energy budgets
5157893	1992	108	4.91	MRIGlobal (NREL)	Compact vacuum insulation
7269966	2007	49	4.82	AIL Research	Heat and mass exchanger
6037032	2000	94	4.75	Lockheed Martin (ORNL)	Pitch-based carbon foam heat sink with phase change material
6711470	2004	100	3.75	Bechtel BWXT Idaho (INL)	Method, system and apparatus for monitoring and adjusting the quality of indoor air
4825939	1989	53	3.29	Univ Dayton	Polymeric compositions incorporating polyethylene glycol as a phase change material
4189848	1980	43	3.17	US Dept Energy	Energy-efficient regenerative liquid desiccant drying process
6751964	2004	42	3.14	Semco Instruments	Desiccant-based dehumidification system and method
6791836	2004	57	3.07	IBM	Smart fan modules and system

Figure 4-22 – Examples of Highly-Cited BTO-funded HVAC Patents



The Citation Indexes in Table 4-5 are based on a single generation of citations to BTO-funded HVAC patents. Tables 4-6 and 4-7 extend this by examining a second generation of citations – i.e. they show the BTO-funded HVAC patents linked via citations to the largest number of subsequent patent families.[14] These subsequent families are divided into two groups, according to whether they are within or beyond HVAC technology. This provides insights into which BTO-funded patent families have been particularly influential within HVAC technology, and which have had a broader impact beyond HVAC.

Table 4-6 contains older BTO-funded HVAC patent families (i.e. with priority dates prior to 1999) linked via citations to the largest number of subsequent patent families. This table is headed by a patent family (representative patent US #5,272,017) assigned to MRIGlobal, through its management of NREL. This patent family, which describes ultra-thin insulation panels, contains the highly cited patent highlighted above in Table 4-5. It is linked to 646 subsequent patent families, only 29 of which are related to HVAC, with many of the remaining patent families describing advanced materials, notably insulated glass. The patent family in second place (representative patent US #4,825,939) is assigned to the University of Dayton, and describes phase change materials that can be used to help regulate building temperatures. It is linked via citations to 588 subsequent patent families, only 30 of which are related to HVAC, with many of the remainder describing materials for apparel, food and medical applications. There are patent families in Table 4-6 with more extensive links to subsequent HVAC families, notably an Atlantic Richfield family (representative patent US #4,217,765) for a heat exchanger and a DOE family (representative patent US #4,732,008) outlining an absorption chiller.

[14] The BTO-funded patent families are divided into two tables based on their age, since older patents tend to be connected to larger numbers of subsequent patents, simply because there has been more time for them to become linked to future generations of technology.

Table 4-6 – Pre-1999 BTO-funded HVAC Patent Families Linked via Citations to Largest Number of Subsequent HVAC/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked HVAC Fams	Assignee	Title
24135744	1988	5157893	646	29	MRIGlobal (NREL)	Compact vacuum insulation
24592876	1984	4825939	588	30	Univ Dayton	Polymeric compositions incorporating polyethylene glycol as phase change material
22238755	1997	6037032	581	20	Lockheed Martin (ORNL)	Pitch-based carbon foam heat sink with phase change material
21937614	1979	4217765	369	131	Atlantic Richfield	Heat exchanger-accumulator
24605606	1984	4540501	341	52	US Dept Energy	Gas hydrate cool storage system
25464707	1986	4732008	324	198	US Dept Energy	Triple effect absorption chiller with two refrigeration circuits
26784440	1977	4312188	304	54	Consolidated Natural Gas	Heat pump system
26686737	1993	5372016	278	99	Climate Master	Ground source heat pump system comprising modular subterranean heat exchange
24547240	1990	5056588	242	59	Instatherm	Evaporative cooling enhanced cold storage system

Table 4-7 contains newer BTO-funded patent families, with priority dates from 1999 onwards. That said, most of these families are still relatively old, dating from the very start of this century.

Table 4-7 – Post-1998 BTO-funded HVAC Patent Families Linked via Citations to Largest Number of Subsequent HVAC/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked HVAC Fams	Assignee	Title
24881021	2000	6711470	457	217	Bechtel BWXT Idaho (INL)	Method and system for monitoring and adjusting the quality of indoor air
68499875	2001	6592449	357	40	IBM	Smart fan modules and system
23572226	1999	6257011	342	17	UT-Battelle (ORNL)	Personal cooling apparatus and method
25465655	2001	6430935	174	13	UT-Battelle (ORNL)	Personal cooling air filtering device
21800925	2001	6778945	146	90	Battelle Mem Inst (PNNL)	Rooftop package unit diagnostician
29779309	2002	6751964	120	73	Semco Instruments	Desiccant-based dehumidification system
32325798	2002	7016742	114		Battelle Mem Inst (PNNL)	Decision support for operations and maintenance
26908238	2000	6568466	72	37	AIL Research	Heat exchange assembly
40901366	2008	8769971	69	53	Alliance Sustain Energy (NREL)	Indirect evaporative cooler using membrane-contained, liquid desiccant
28452518	2002	6868678	63	39	UT-Battelle (ORNL)	Non-intrusive refrigerant charge indicator

Three patent families stand out in Table 4-7 in terms of their number of citation links to subsequent patent families. The first is the Bechtel BWXT (INL) air quality patent family containing the highly-cited patent (US #6,711,470) highlighted earlier in Table 4-5. This patent family is linked via citations to 457 subsequent patent families, almost half of which are related to HVAC. The patent families in second and third place in Table 4-7 have much more extensive citation links beyond HVAC than within it. The second-placed patent family (representative patent US #6,592,449) is assigned to IBM and describes fans for cooling computer components. It is linked via citations to 357 subsequent patent families, only 40 of which are within HVAC, with many of the remainder being related to cooling technologies for computer, semiconductor and electronic devices. The patent family in third place in Table 4-7 (representative patent US #6,257,011) is assigned to UT-Battelle, through its management of Oak Ridge National Laboratory (ORNL), and describes a cooling system designed for use in body armor. It is linked via citations to 342 subsequent patent families, all but seventeen of which are from beyond HVAC, with many of them related to apparel and medical applications.

The tables above identify BTO-funded patent families linked particularly strongly to subsequent technological developments. Table 4-8 looks in the opposite direction, and identifies highly-cited patents linked to earlier BTO-funded HVAC patents. The patents in Table 4-8 are examples where BTO-funded HVAC research has formed part of the foundation for subsequent high-impact technologies. This table focuses on patent families not owned by the leading HVAC companies, since those families were examined in the backward tracing element of the analysis.

Table 4-8 - Highly Cited Patents (not from leading HVAC Companies) Linked via Citations to Earlier BTO-funded HVAC Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
6230501	2001	349	20.04	ProMDX Technology	Ergonomic systems and methods providing intelligent adaptive surfaces and temperature control
8516842	2013	81	19.47	Gentherm Inc	Thermal conditioning system for climate-controlled seat assemblies
6441943	2002	435	15.21	Gentex Corp	Indicators and illuminators using a semiconductor radiation emitter package
5982553	1999	437	14.38	Screen Holdings Co	Display device incorporating one-dimensional grating light-valve array
8147599	2012	58	13.48	McAlister Technologies	Apparatuses and methods for storing and/or filtering a substance
8009001	2011	87	12.81	Boeing Co.	Hyper halbach permanent magnet arrays
7244294	2007	134	12.28	Emerson Electric Co.	Air filter monitoring system
6855410	2005	158	11.95	NASA	Phase change material thermal capacitor clothing
7416137	2008	130	11.16	Vast Power Systems Inc	Thermodynamic cycles using thermal diluent
7832207	2010	94	10.58	General Compression	Systems and methods for energy storage and recovery using compressed gas

The patents in Table 4-8 are assigned to a variety of organizations, and describe many different technologies. The patent at the head of this table (US #6,230,501) is assigned to ProMDX Technology and has been cited as prior art by over 349 subsequent patents, twenty times as many citations as expected. This patent, which was granted in 2001, describes an ergonomic system incorporating temperature control. It is one of a number of older patents in Table 4-8 that have

been cited by large numbers of subsequent patents. Other examples include a Gentex patent (US #6,441,943) for an LED vehicle lamp with a heat extraction member and a Screen Holdings patent (US #5,982,553) describing miniature displays with lower power consumption. Table 4-8 also includes a number of more recent patents, including a 2013 Gentherm patent (US #8,516,842) outlining climate control for vehicle seats and a 2012 McAlister Technologies patent (US #8,147,599) describing a sorption media that can be heated to filter and store substances.

As with the backward tracing element of the analysis, the patent-level results from the forward tracing focus on BTO-funded HVAC patents. That said, within the forward tracing, we did also identify Other DOE-funded HVAC patent families linked to the largest number of subsequent patent families within and beyond HVAC technology. These Other DOE-funded HVAC families are shown in Table 4-9.

Table 4-9 - Other DOE-funded HVAC Patent Families Linked via Citations to Largest Number of Subsequent HVAC/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked HVAC Fams	Assignee	Title
25132602	1977	4182398	633	29	US Dept Energy	Crosslinked crystalline polymer and methods for cooling and heating
22492449	1980	4336692	394	170	Atlantic Richfield	Dual source heat pump
22699825	1998	6193601	358	72	Sandia Corp	Module bay with directed flow
25373255	1978	4176523	258	129	Garrett Corp	Adsorption air conditioner
25294139	1997	5848532	253	0	American Superconductor Corp	Cooling system for superconducting magnet
46204872	2002	6880344	244	11	UTC Power LLC	Combined rankine and vapor compression cycles
22706171	1980	4355522	184	29	US Dept Energy	Passive ice freezing-releasing heat pipe
26784369	1979	4532778	175	32	Rocket Research Corp	Chemical heat pump and chemical energy storage system
21803405	1979	4280333	146	10	US Dept Energy	Passive environmental temperature control system
23743315	1999	6230503	103	28	Sandia Corp	Method and apparatus for extracting water from air

The patent family at the head of Table 4-9 (representative patent US #4,182,398) is assigned to DOE and is one of the earliest DOE-funded families in the analysis, having been filed in 1977. It describes crystalline polymers that can be used in heat storage applications, for example in absorption air conditioning or solar energy. This DOE family is linked via citations to 633 subsequent patent families, only 29 of which are related to HVAC technology, with many of the remainder describing advanced materials. The second patent family in Table 4-9 (representative patent US #4,336,692) is assigned to Atlantic Richfield and describes a heat pump for HVAC systems. This patent family, which was filed in 1980, was highlighted earlier in the backward tracing element of the analysis (see Table 4-4). It is linked via to 394 subsequent patent families, 170 of which are related to HVAC. The third patent family in Table 4-9 (representative patent

US #6,193,601) is more recent, having been filed in 1998. This patent family is assigned to Sandia and describes a module bay with reduced air flow, especially for use in semiconductor processing. It is linked via citations to 358 subsequent patent families, many related to cooling, especially for electronic components and data centers.

The forward tracing element of the analysis shows that BTO-funded and Other DOE-funded HVAC patents are linked via citations to subsequent patents assigned to a number of very large companies. The influence of BTO-funded and Other DOE-funded HVAC research can be seen both within HVAC technology and across a range of other technologies, including advanced materials, solar thermal energy, computing, and semiconductor manufacturing.

Overall, the results from the HVAC analysis suggest that DOE-funded patenting in this technology been relatively consistent over time, with BTO-funded patents representing a high percentage of the total. Given their comparatively small size, the portfolios of BTO-funded and Other DOE-funded HVAC patents have had a notable influence on subsequent innovations associated with the leading companies in HVAC technology. The influence of these patents also extends beyond HVAC into other technologies, including advanced materials, solar thermal energy and semiconductor manufacturing.

5. Results – Appliances

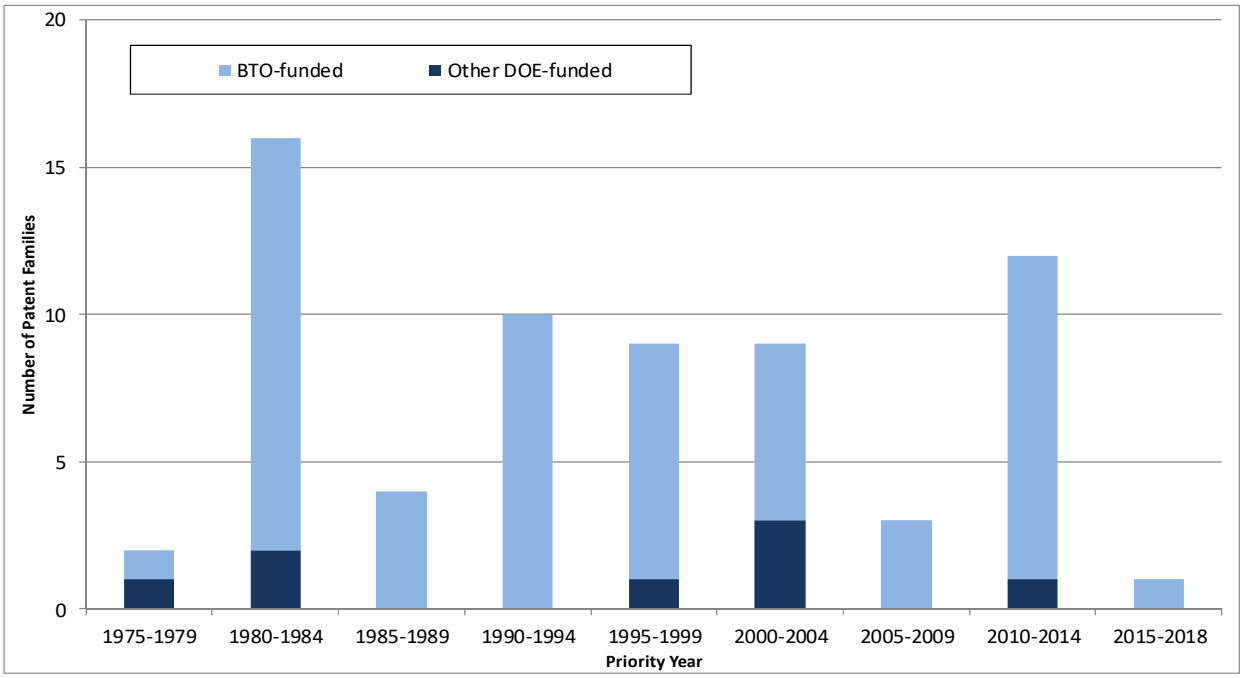
This section of the report outlines the results of our analysis tracing the influence of BTO-funded and Other DOE-funded appliance research on subsequent developments both within and beyond appliance technology. The results are divided into three main sections. In the first section, we examine trends in patenting over time in appliances, and assess the distribution of BTO-funded and Other DOE-funded patents across appliance technologies. The second section then reports the results of an analysis tracing backwards from appliance patents owned by the leading companies in this technology. The purpose of this analysis is to determine the extent to which appliance innovations developed by leading companies build upon earlier appliance research funded by BTO (plus appliance research funded by the remainder of DOE). In the third section, we report the results of an analysis tracing forwards from BTO-funded (and Other DOE-funded) appliance patents. The purpose of this analysis is to assess the broader influence of DOE-funded research upon subsequent developments within and beyond appliance technology.

Overall Trends in Appliance Patenting

Trends in Appliance Patenting over Time

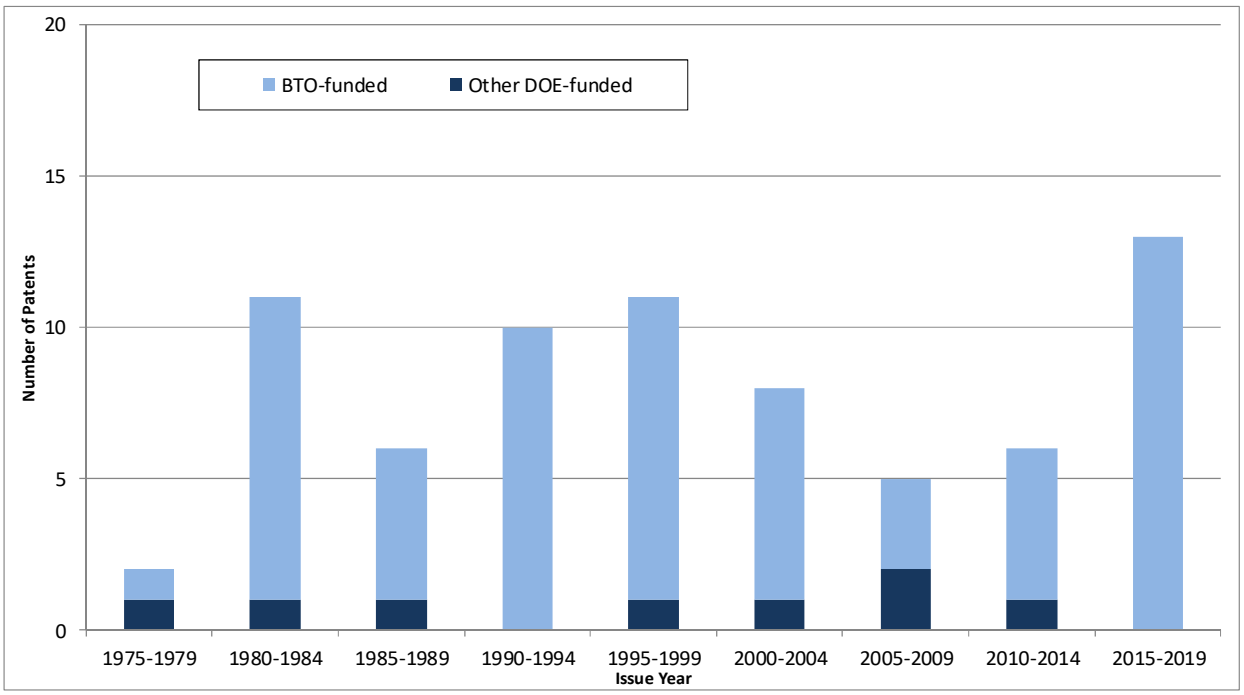
Figure 5-1 shows the number of BTO-funded and Other DOE-funded appliance patent families by priority year – i.e. the year of the first application in each patent family. This figure reveals that there is no clear trend in DOE-funded appliance patenting over time. The numbers of patent families are relatively low, peaking at sixteen in 1980-1984 and twelve in 2010-2014. The numbers of patent families between those time periods are lower, only reaching four in 1985-1989 and three in 2005-2009. BTO-funded patent families represent a high percentage of the total (58 out of 66 DOE-funded appliance patent families overall).

Figure 5-1 - Number of Appliance Patent Families funded by BTO and Other DOE Sources by Priority Year (5-Year Totals)



Note: The final time period in this figure is 2015-2018, and is shown for completeness, although data for this time period are incomplete. Our primary data collection covered only patents issued through 2018. Due to time lags associated with the patenting process, only a fraction of the patent families from 2015-2018 will be included.

Figure 5-2 - Number of DOE-Funded Appliance Granted U.S. Patents by Issue Year (5-Year Totals)

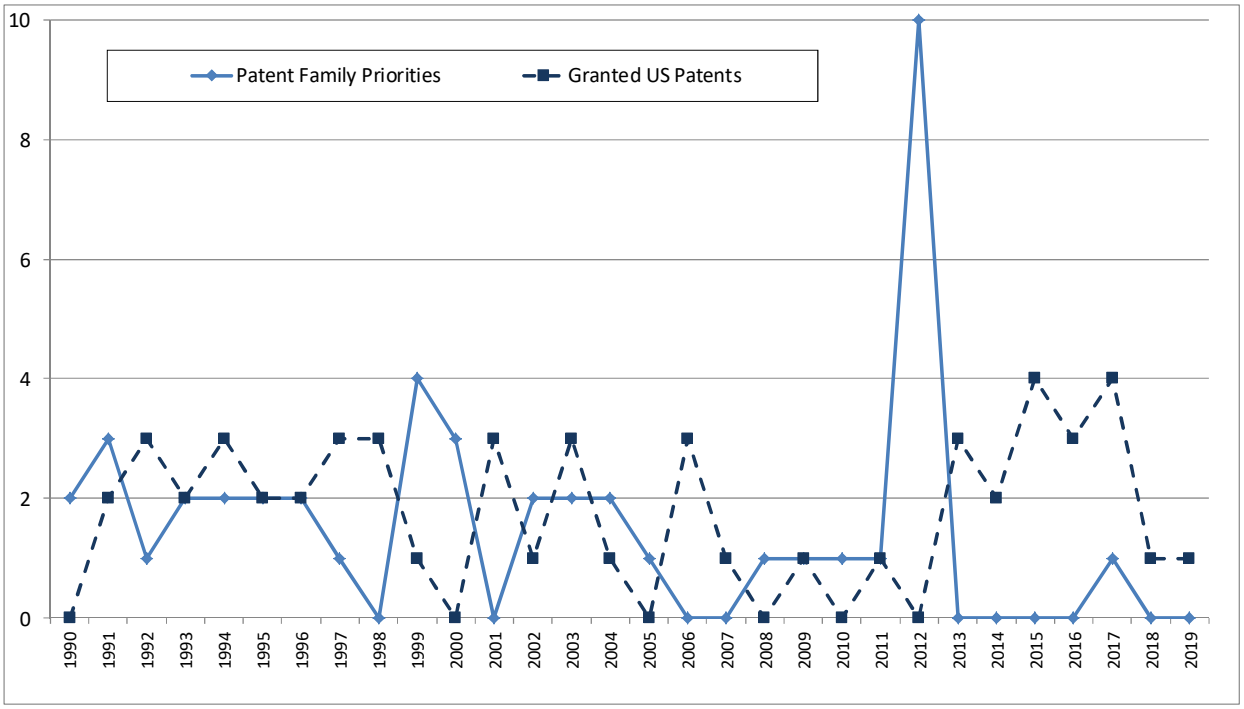


Note: The data collection period for this analysis ended with 2018. Any 2019 patents in the 2015-2019 column are additional patents that have been included because they are members of the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

Figure 5-2 shows the number of BTO-funded and Other DOE-funded appliance granted U.S. patents. This figure follows a similar pattern to Figure 5-1, with no overall trend in the number of DOE-funded appliance patents. There are four periods where the number of patents reached double figures (11 in 1980-1984; 10 in 1990-1994; 11 in 1995-1999 and 13 in 2015-2019), interspersed with periods with lower numbers of patents. As in Figure 5-1, BTO-funded patents represent a high percentage of the total number of DOE-funded appliance U.S. patents.

Comparing Figures 5-1 and 5-2 shows the effect of time lags in the patenting process. For example, many of the patent families with priority dates in 2010-2014 (Figure 5-1) resulted in granted U.S. patents in 2015-2019 (Figure 5-2). These time lags can also be seen in Figure 5-3, which shows appliance patent family priority years and issue years for granted U.S. appliance patents (in this figure, BTO and Other DOE are combined, in order to simplify the presentation). The number of patent families and granted U.S. patents both have little consistent pattern throughout the early years shown in this figure (which is restricted to 1990 onwards for presentation purposes). There is then a spike in patent families in 2012, with a corresponding increase in the number of granted U.S. patents between 2015 and 2017.

Figure 5-3 - Number DOE-funded Appliance Patent Families (by Priority Year) and Granted U.S. Patents (by Issue Year)

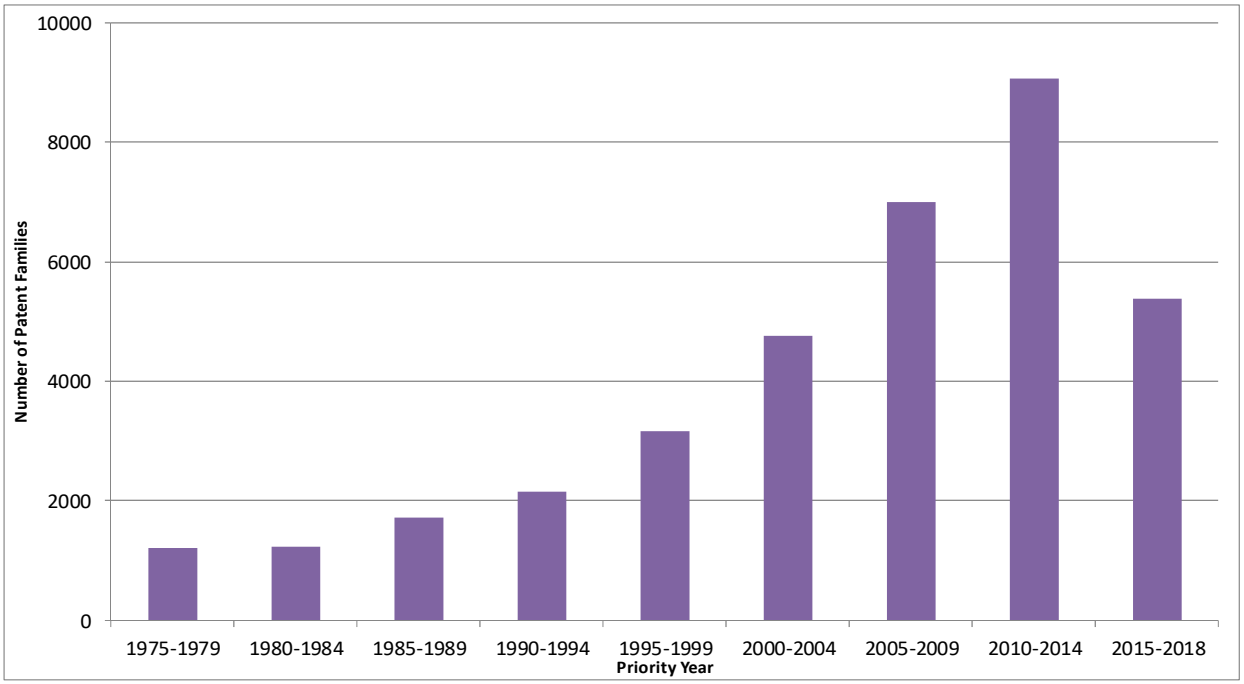


Note: The data collection period for this analysis ended with 2018. The 2019 patents are included because they are part of the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

Figures 5-1 – 5-3 focus on DOE-funded appliance patent families. Figure 5-4 broadens the scope, and shows the overall number of appliance patent families by priority year (based on USPTO, EPO, and WIPO filings). This figure shows a much more distinct trend in overall appliance patenting than that associated with DOE-funded patenting. The number of appliance patent families was relatively consistent between 1975 and 1984, averaging 200-250 families per year (around 1,200 per 5-year period). The number of patent families then started to increase,

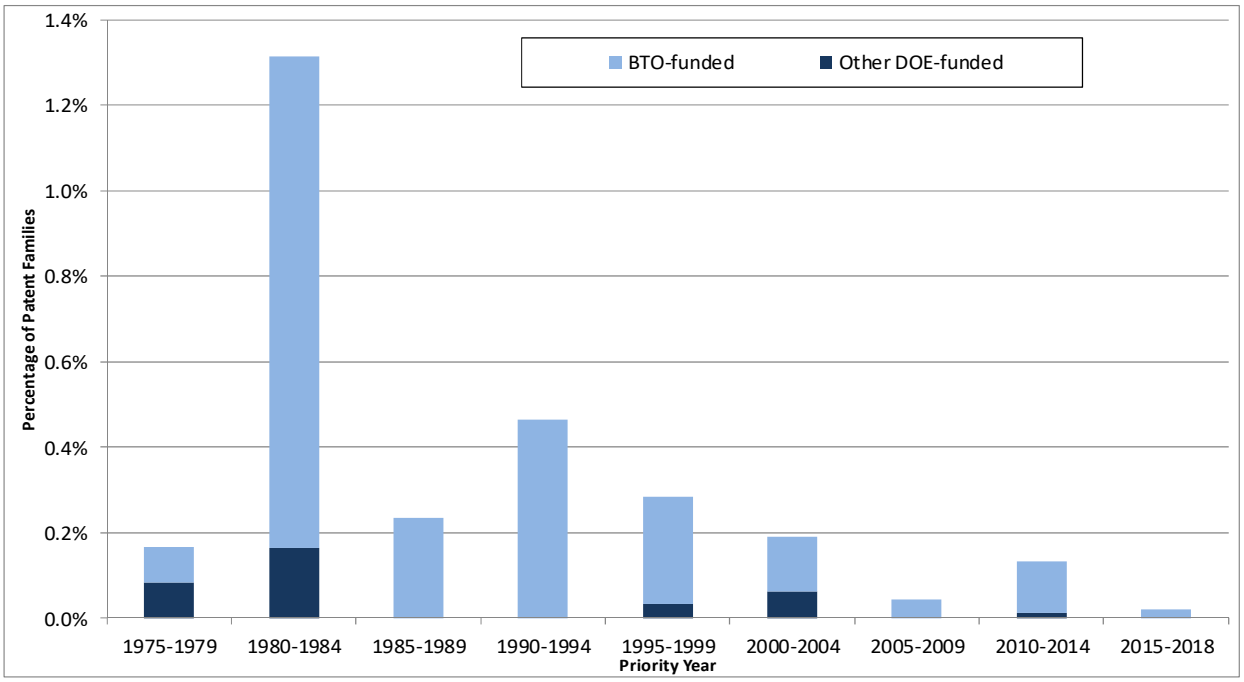
and grew in each time period, peaking at 9,070 in 2010-2014. Hence, more than seven times as many appliance patent families were filed in 2010-2014 as in 1980-1984. The number of patent families fell in 2015-2018, but data for this period are incomplete (see note below Figure 5-4).

Figure 5-4 - Total Number of Appliance Patent Families by Priority Year (5-Year Totals)



Note: The final time period in this figure is 2015-2018. Data for this time period are incomplete. Due to time lags associated with the patenting process, only a fraction of the patent families from this time period will be included.

Figure 5-5 - Percentage of Appliance Patent Families Funded by DOE by Priority Year



Note: The final time period in this figure is 2015-2018. Data for this time period are incomplete. Due to time lags associated with the patenting process, only a fraction of the patent families from this time period will be included.

Figure 5-5 shows the percentage of appliance patent families in each time period that were funded by DOE (BTO plus Other DOE). The figure reveals that the percentage peaked at 1.3% in 1980-1984, but has not been above 0.5% in any period since. This finding is not surprising, since the overall number of appliance patent families has increased markedly over time, while the number of DOE-funded appliance families has been relatively consistent. Overall, 0.18% of patent families in the period 1976-2018 were funded by DOE.

Leading Appliance Assignees

The ten leading patenting companies in appliance technology are listed above in Table 3-6, along with their number of appliance patent families. Figure 5-6 shows the same information in graphical form, while also including DOE-funded patent families.

Figure 5-6 – Leading Appliance Companies (based on number of patent families)

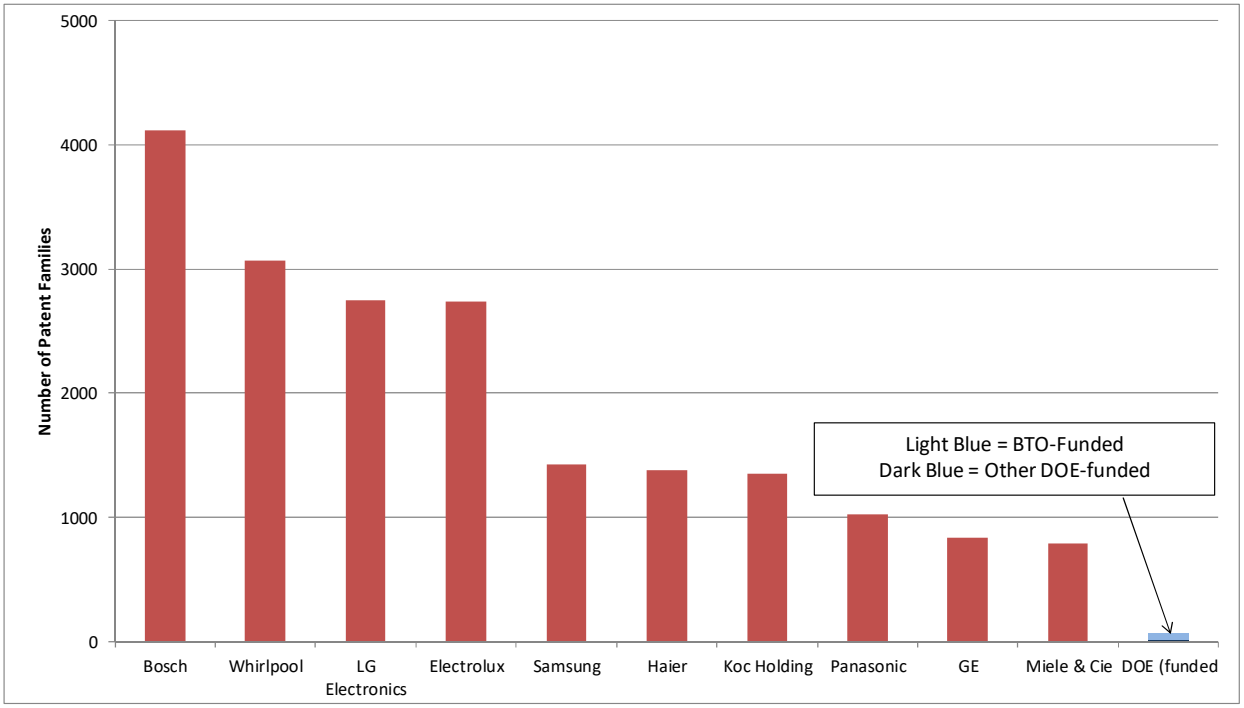


Figure 5-6 reveals that, among the leading companies, Bosch has the largest appliance patent portfolio, containing 4,117 patent families. It is followed by Whirlpool (3,071 families), LG Electronics (2,753) and Electrolux (2,740). One notable feature of Figure 5-6 is the geographical distribution of the leading companies, with four from Asia, four from Europe and two from North America. This reinforces the earlier point that, while the analysis does not include patents from Asian systems, this does not mean that patents associated with Asian companies are excluded.

The DOE-funded appliance patent portfolio of 66 patent families (58 BTO-funded; eight Other DOE-funded) is much smaller than the portfolios associated with the leading appliance companies in Figure 5-6. In evaluating the influence of DOE-funded appliance patents versus the influence of patents owned by the leading companies, we therefore take this difference in

portfolio size into account. It should also be noted that there is a small amount of double-counting of patent families in Figure 5-6. Specifically, there are ten Whirlpool appliance patent families that were funded at least in part by BTO. These ten families are counted in both the Whirlpool column and the BTO segment of the DOE-funded column in Figure 5-6. This double counting is appropriate, since these families are both funded by BTO and assigned to Whirlpool.

Assignees of BTO/Other DOE Appliance Patents

The DOE-funded appliance patent portfolios are constructed somewhat differently from the portfolios of the top twelve companies listed in Figure 5-6. Specifically, DOE's 66 patent families are those funded by DOE, but they are not necessarily assigned to the agency. For example, BTO (or another DOE office) may have partially or fully funded research projects at DOE labs or companies. In such cases, the assignees of any resulting patents may be the DOE lab managers or companies (as with the ten Whirlpool families referred to above).

Figure 5-7 shows the leading assignees on BTO-funded appliance patent families. This figure is headed by DOE itself, which has thirteen BTO-funded patent families assigned to it. Such an assignment may occur for various reasons, including where the inventors are federal employees; where the funding recipient elects not to pursue patent protection for, or take title to, the invention; or where the funding recipient does not have the right to take title to the invention. Whirlpool is in second place in Figure 5-7 with ten patent families, as discussed above. The remaining organizations in this figure are DOE lab managers, with managers associated with Oak Ridge National Laboratory (Lockheed Martin and UT-Battelle) featuring in third and fourth place.

Figure 5-7 - Assignees with Largest No. of BTO-Funded Appliance Patent Families

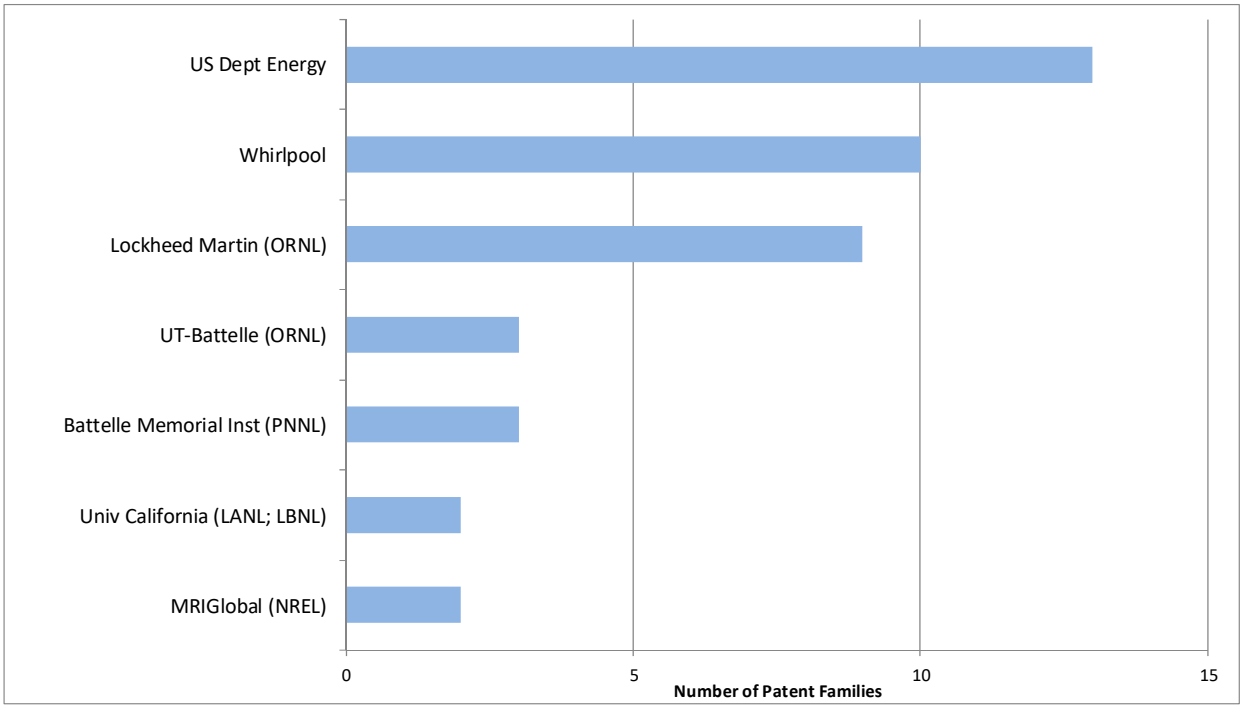
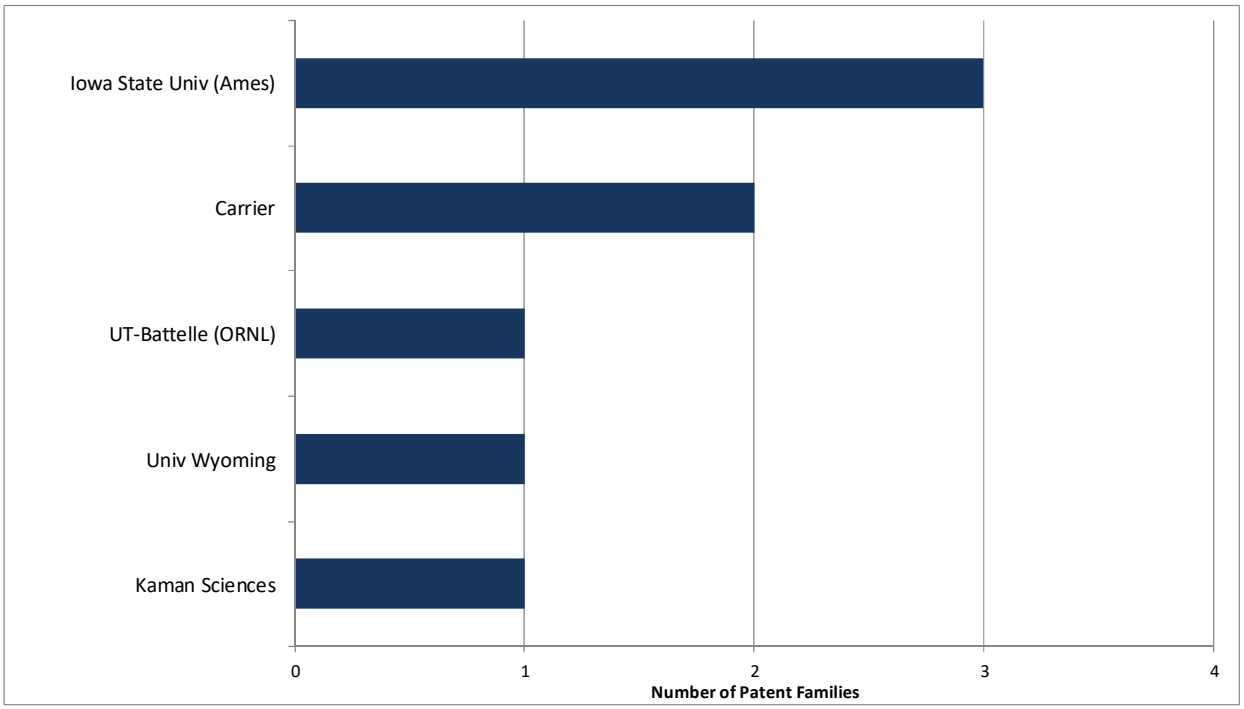


Figure 5-8 lists the assignees on Other DOE-funded appliance patent families (since there are only eight such families, all assignees are shown in this figure). The list is headed by Iowa State University with three patent families (through its management of Ames National Laboratory), following by Carrier with two families. The three remaining organizations in Figure 5-8 – UT Battelle (through its management of Oak Ridge National Laboratory), University of Wyoming, and Kaman Sciences – each has one Other DOE-funded appliance patent family.

Figure 5-8 - Assignees with Largest No. of Other DOE-funded Appliance Patent Families



Distribution of Appliance Patents across Patent Classifications

We analyzed the distribution of BTO-funded appliance U.S. patents across Cooperative Patent Classifications (CPCs).[15] We then compared this distribution to those associated with Other DOE-funded appliance patents; appliance patents assigned to the ten leading companies; and the universe of all appliance patents. This analysis provides insights into the technological focus of BTO funding in appliances, versus the focus of the remainder of DOE, leading appliance companies, and appliance technology in general. The results from this CPC analysis are shown in two separate charts, each from a different perspective.

The first chart (Figure 5-9) is based on the six CPCs that are most prevalent among BTO-funded appliance patents. The purpose of this chart is thus to show the main focus areas of BTO-funded appliance research, and the extent to which these areas translate to other portfolios (Other DOE-funded; leading appliance companies; all appliance patents). This figure reveals that BTO-funded patents are focused almost entirely on refrigeration and cooling, specifically absorption and

[15] The CPC is a patent classification system. Patent offices attach numerous CPC classifications to a patent, covering the different aspects of the subject matter in the claimed invention. In generating these charts, all CPCs associated with each patent are included.

magnetic refrigeration, plus refrigeration compressors. The leading companies, and appliance patents in general, have very little presence in these technologies.

Figure 5-9 - Percentage of Appliance U.S. Patents in Most Common Cooperative Patent Classifications (Among BTO-Funded Patents)

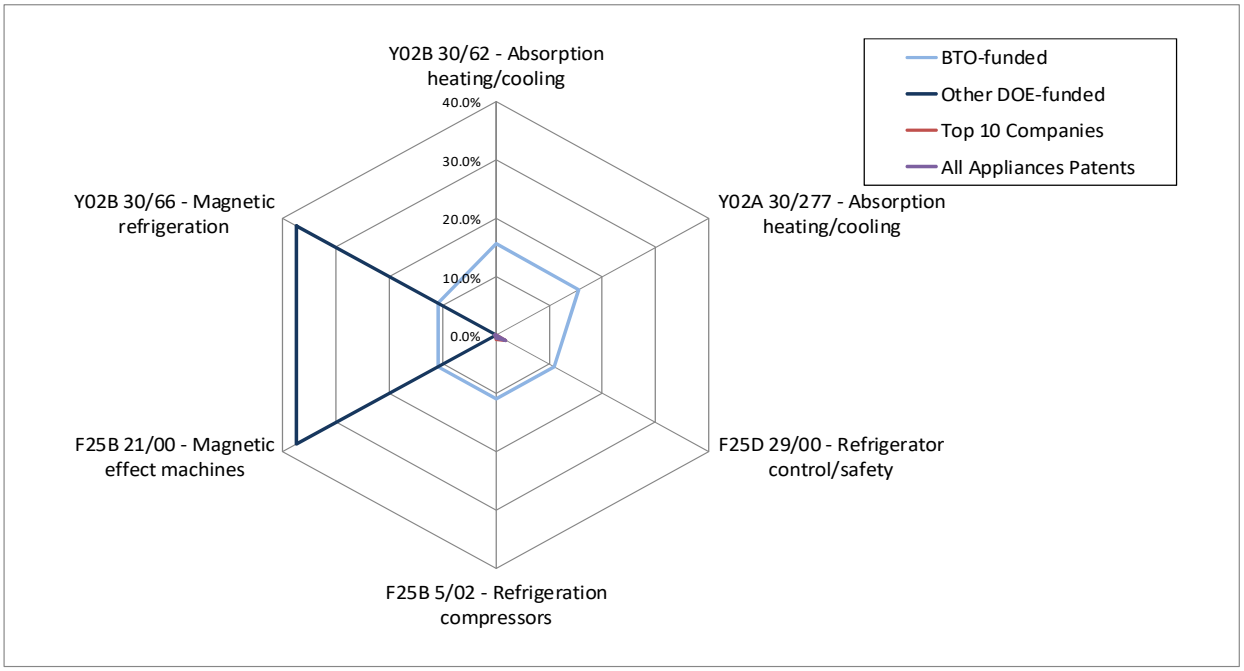


Figure 5-10 - Percentage of Appliance U.S. Patents in Most Common Cooperative Patent Classifications (Among All Appliance Patents)

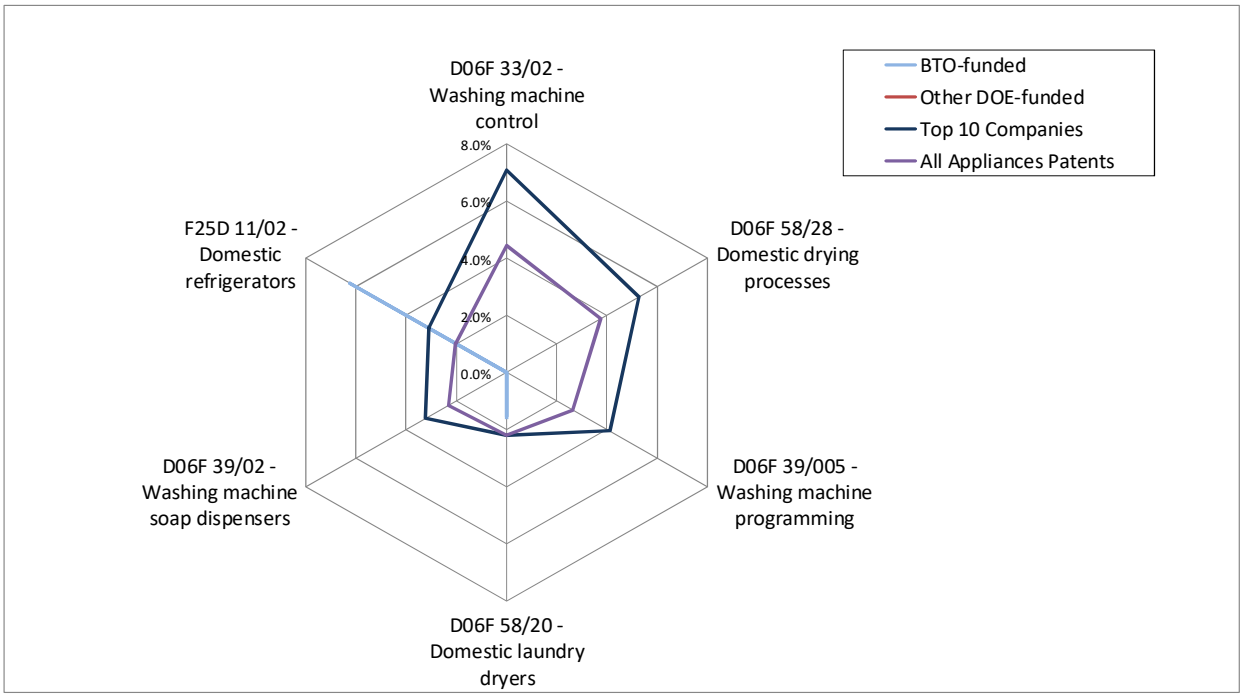
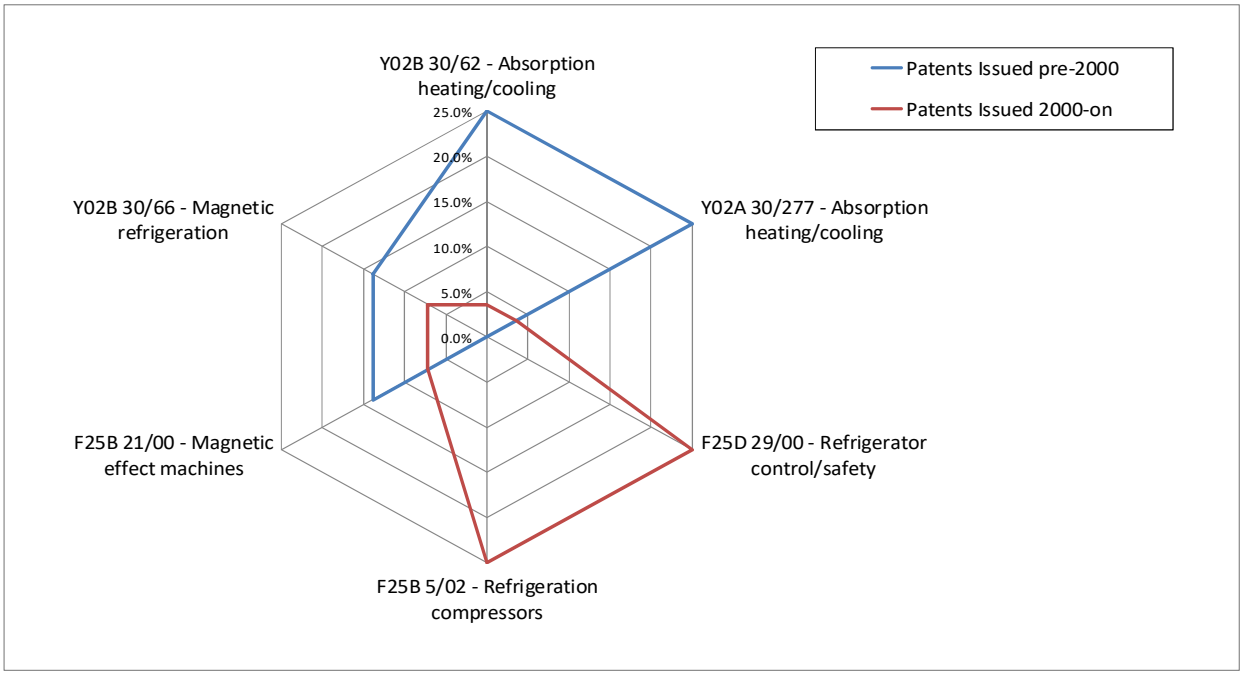


Figure 5-10 is similar to Figure 5-9, except that it is from the perspective of the most common CPCs among all appliance patents. Hence, the purpose of this chart is to show the main research areas within appliances as a whole, and how these areas are represented in selected appliance portfolios (BTO-funded; Other DOE-funded; leading appliance companies). There is no overlap between the CPCs in Figures 5-9 and 5-10. The latter figure focuses on CPCs related to washing machines and domestic dryers, technologies where the BTO-funded and Other DOE-funded patent portfolios have very little presence. There is one CPC in Figure 5-10 where there are some BTO-funded patents – F25D 11/02 (Domestic refrigerators). Overall, Figures 5-9 and 5-10 suggest that the appliance technologies developed by recipients of DOE funding have had a different primary focus to those pursued by the leading appliance companies.

Figure 5-11 compares the CPC distribution of BTO-funded appliance U.S. patents across two time periods – patents issued through 1999, and those issued from 2000 onwards. This figure reveals that the focus of BTO-funded appliance patents shifted markedly between the two time periods. In the earlier time period, their emphasis was on absorption heating and cooling (CPCs Y02A 30/277 and Y02B 30/62), while the more recent period is characterized by patents related to refrigerator compressors and safety (CPCs F25B 5/02 and F25D 29/00).

Figure 5-11 - Percentage of BTO-funded Appliance U.S. Patents in Most Common Cooperative Patent Classifications across Two Time Periods



Tracing Backwards from Appliance Patents Owned by Leading Companies

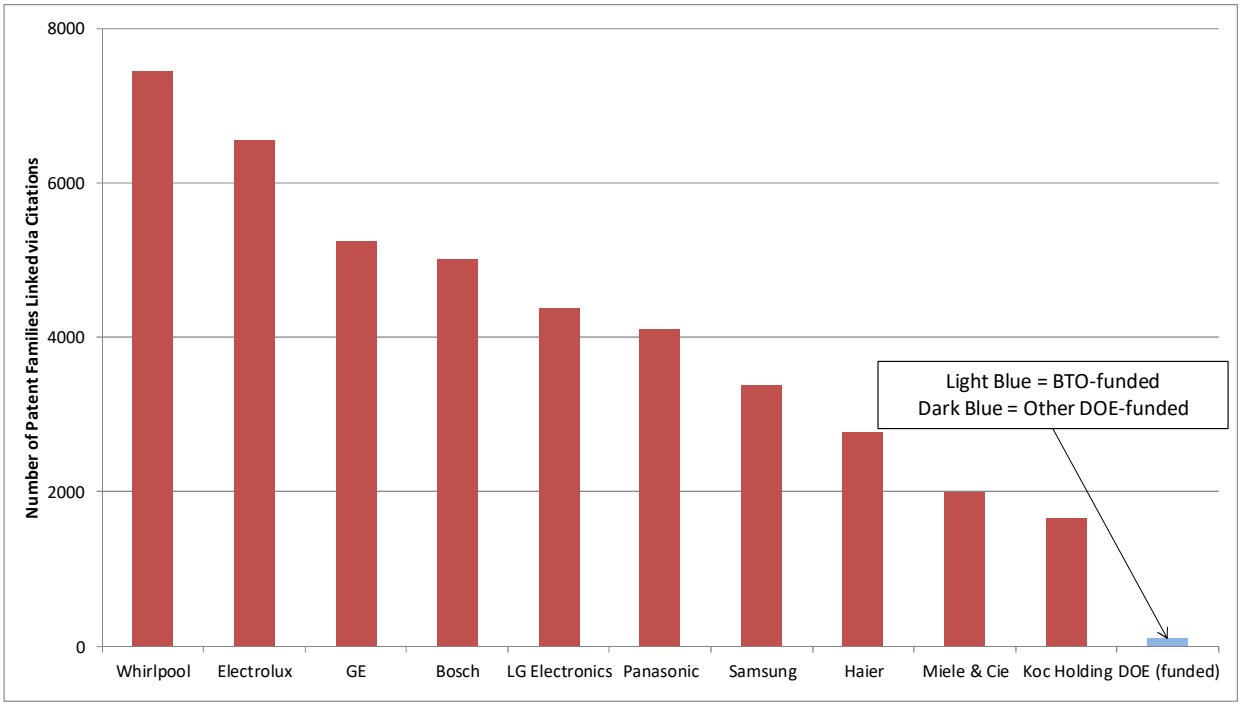
This section reports the results of an analysis tracing backwards from appliance patents owned by leading companies in this technology to earlier research, including that funded by BTO (and by DOE in general). The results in this section are examined at two levels. First, we report results at the organizational level. These results reveal the extent to which BTO-funded (and Other DOE-funded) research forms a foundation for subsequent innovations associated with leading appliance companies. Second, we drill down to the level of individual patents, with a particular

focus on BTO-funded appliance patents. These patent-level results highlight specific BTO-funded patents that are linked extensively via citations to subsequent patents owned by leading companies. They also highlight which appliance patents owned by these leading companies are linked most extensively via citations to earlier BTO-funded research.

Organizational Level Results

In the organizational level results, we first compare the influence of BTO-funded and Other DOE-funded appliance research against the influence of leading companies in this technology. We then identify which of these leading companies build most extensively on DOE-funded appliance research. Figure 5-12 compares the influence of BTO-funded and Other DOE-funded appliance research to the influence of research carried out by the ten leading appliance companies. Specifically, this figure shows the number of appliance patent families owned by the leading companies that are linked via citations to earlier appliance patent families assigned to each of these leading companies (plus patent families funded by DOE). This figure thus shows the companies whose patents have had the strongest influence upon subsequent innovations associated with the leading appliance companies.[16]

Figure 5-12 - Number of Leading Company Appliance Patent Families Linked via Citations to Earlier Appliance Patents from each Leading Company (e.g. 105 leading company families are linked to earlier BTO/Other DOE-funded families)



[16] This figure compares the influence of patents *funded* by BTO/Other DOE against patents *owned* by (i.e. assigned to) organizations. Such a comparison is reasonable, since patents funded by organizations through their R&D budgets will be assigned to those organizations. Also, organizations cannot choose to reference the patents of a non-competitor (such as DOE) rather than the patents of a competitor in order to reduce the "credit" given to that competitor. Such an omission could lead to the invalidation of their patents. Note that, as in Figure 5-6, there is a small amount of double-counting in Figure 5-12, as ten Whirlpool families were funded by DOE. Also, in Figure 5-12 and Figures 5-14 – 5-16, leading company patent families linked to both BTO-funded and Other DOE-funded patents are allocated to the BTO-funded segment of the DOE column, to avoid double-counting these families.

Whirlpool is at the head of Figure 5-12. In total, 7,448 leading company appliance patent families (i.e. 20.8% of these 35,876 families) are linked via citations to earlier Whirlpool patents. Electrolux is in second place, with 6,540 leading company patent families linked to its patents, followed by General Electric (5,241 families) and Bosch (5,017 families). DOE-funded patents are in last place in Figure 5-12, with a total of 105 leading company patent families linked to them (95 of which are linked to BTO-funded patents). At first glance, this does not appear promising in terms of DOE's influence in appliance technology. However, Figure 5-12 does not take into account the different sizes of the patent portfolios associated with the various companies. For example, it is not surprising that many more patent families are linked via citations to Bosch than to DOE, since Bosch has over sixty times as many appliance patent families available to be cited as prior art.

Figure 5-13 takes into account the differences in patent portfolio size. It shows the average (mean) number of leading company patent families linked to patent families associated with each of the leading companies, plus DOE. For example, on average, DOE-funded appliance patent families (the majority of which are BTO-funded) are each linked to 1.6 patent families assigned to the leading companies. This puts DOE-funded patents in eighth place in Figure 5-13 (which is headed by General Electric and Panasonic, whose patent families are linked to an average of 6.2 and 4.0 leading company families respectively). While adjusting for portfolio size improves the ranking of DOE-funded appliance patents, their relatively low position in Figure 5-13 is not unexpected, given that their technological focus is very different to those of the leading companies (as outlined in Figures 5-9 and 5-10).

Figure 5-13 – Average Number of Leading Company Appliance Patent Families Linked via Citations to Appliance Families from Each Leading Company
e.g. on average, each DOE-funded patent family is linked to 1.6 subsequent patent families assigned to leading companies

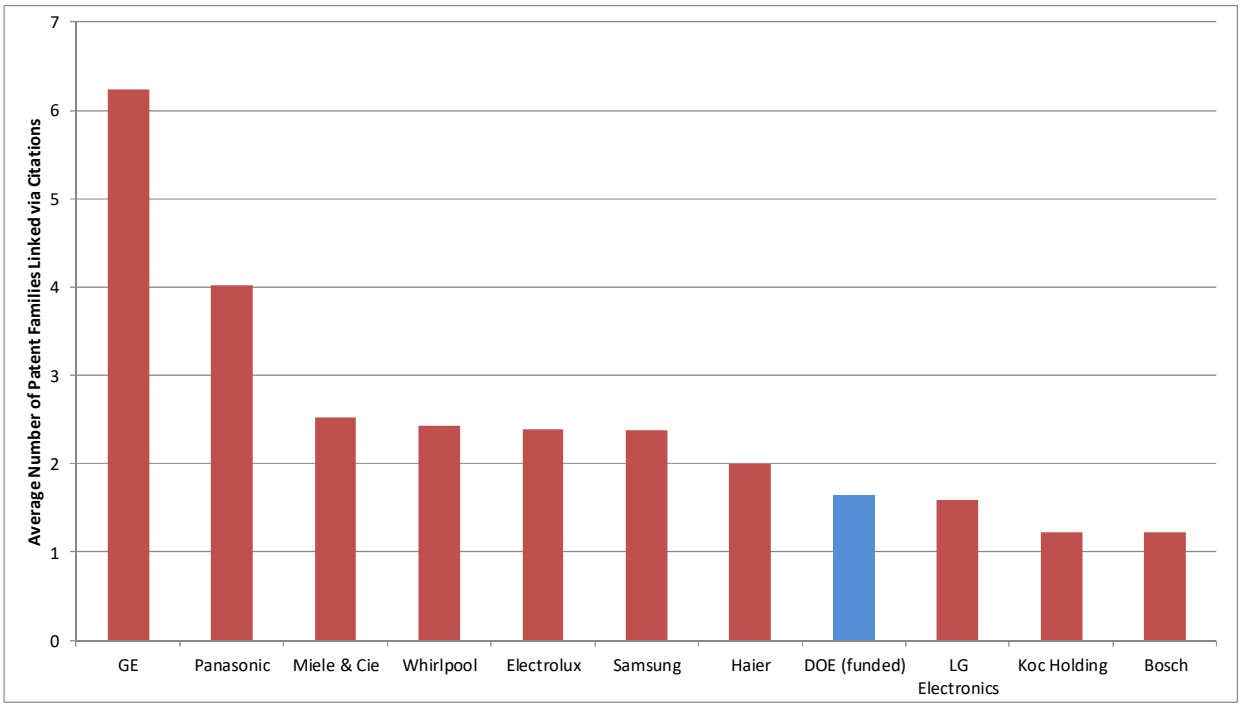


Figure 5-14 shows the number of appliance patent families assigned to each leading company that are linked via citations to earlier BTO-funded and Other DOE-funded patents. This figure reveals that eight out of the ten leading companies have at least one appliance patent family linked via citations to earlier DOE-funded patents, the exceptions being Koc Holding and Miele. Whirlpool is at the head of Figure 5-14, with 47 patent families linked to DOE-funded patents (all of which are linked to BTO-funded patents). Haier is in second place, with 21 patent families linked to DOE (12 to BTO), followed by LG Electronics (12 families linked to DOE; all to BTO) and Bosch (11 families linked to DOE; 10 to BTO).

Figure 5-14 - Number of Patent Families Assigned to Leading Appliance Companies Linked via Citations to Earlier BTO/Other DOE-funded Appliance Patents

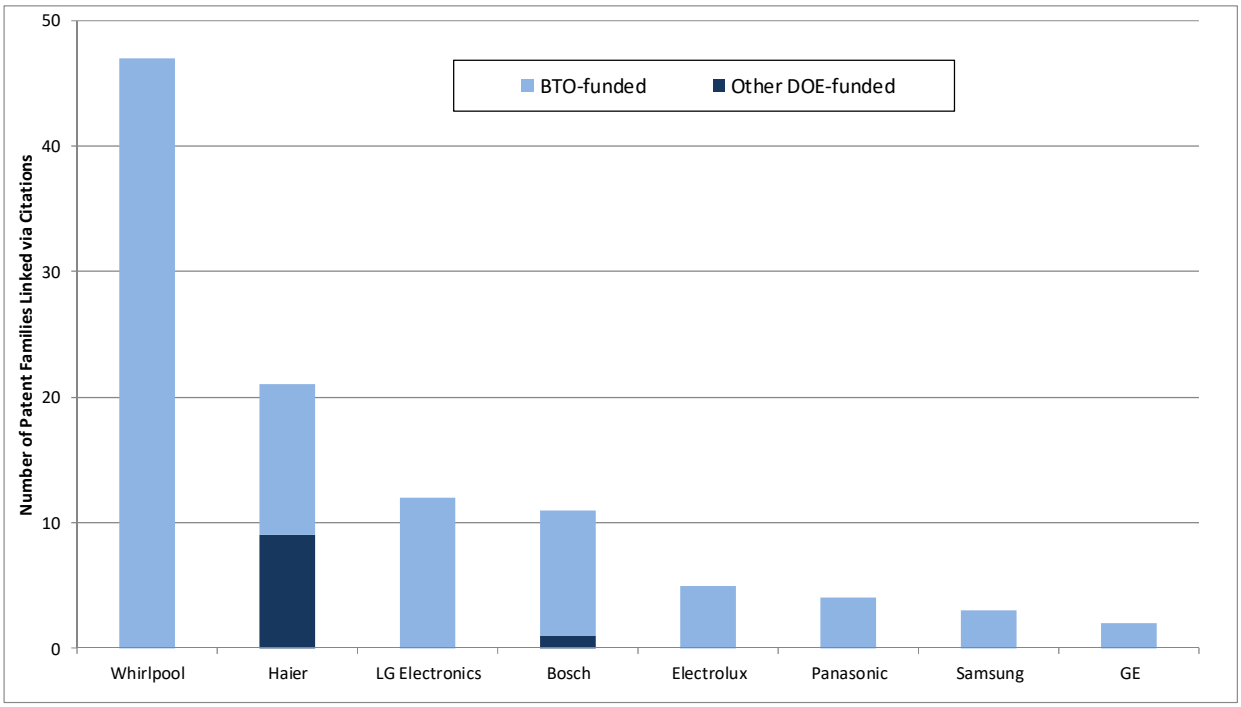


Figure 5-15 counts the total number of citation links from leading companies to earlier DOE-funded patents. This differs slightly from the count of linked families in Figure 5-14, since a single patent family may be linked to multiple earlier DOE-funded patents. Haier is in first place in Figure 5-15, with a total of 93 citation links to DOE-funded appliance patents (75 of which are links to BTO-funded patents). This moves Haier ahead of Whirlpool, which has a total of 83 citation links to DOE-funded patents, all of which are links to BTO-funded patents. These two companies lead the other companies by a wide margin in Figure 5-15.

There is an element of portfolio size bias in the patent family counts in Figures 5-14 and 5-15. Companies with larger appliance patent portfolios are likely to have more patent families linked to DOE, simply because they have more families overall. Figure 5-16 accounts for this portfolio size bias by calculating the percentage of each leading company's appliance patent families that are linked via citations to earlier DOE-funded appliance patents, rather than their absolute number. Hence, this is a measure of how extensively each company builds on DOE-funded research, relative to their overall patent output. Figure 5-16 reveals that, even after accounting

for patent portfolio size, Whirlpool and Haier still have the strongest citation links to earlier DOE-funded (and especially BTO-funded) appliance patents.

Figure 5-15 - Total Number of Citation Links from Leading Appliance Company Patent Families to Earlier BTO/Other DOE-funded Appliance Patents

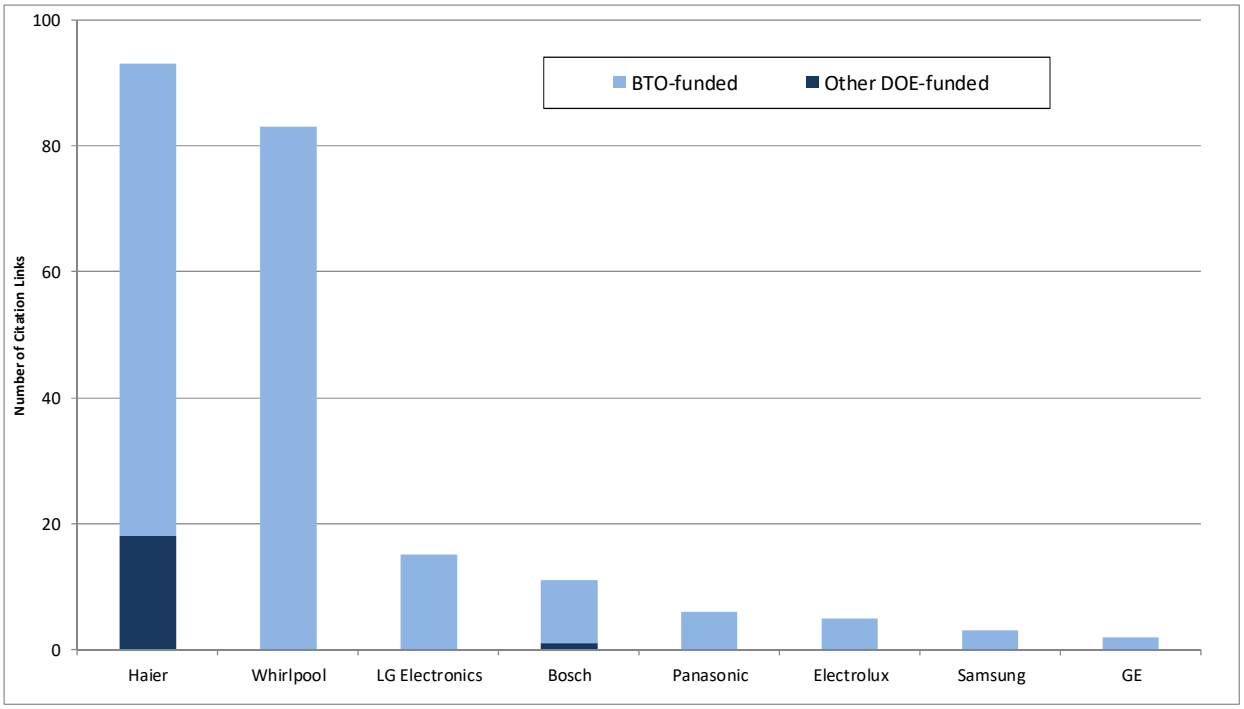
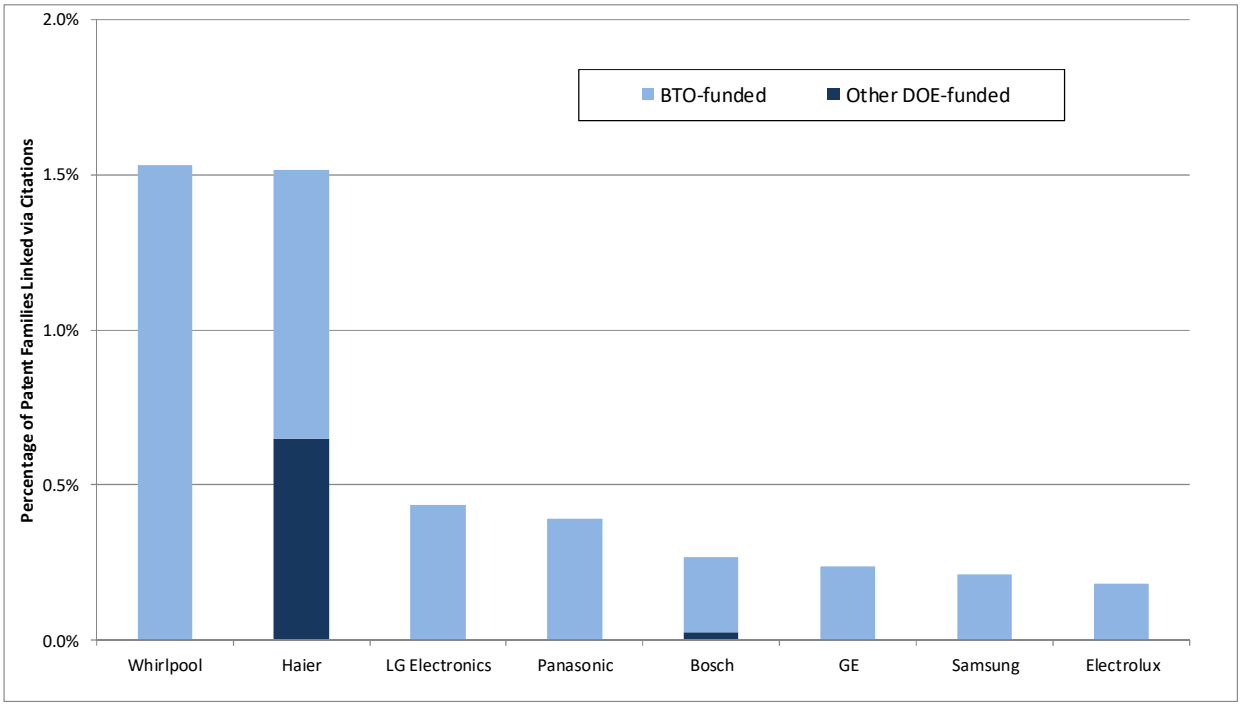


Figure 5-16 - Percentage of Leading Appliance Company Patent Families Linked via Citations to Earlier BTO/Other DOE-funded Appliance Patents



Patent Level Results

The previous section of the report examined results at the level of entire patent portfolios. The purpose of this section is to drill down to identify individual DOE-funded appliance patent families (in particular BTO-funded families) are linked via citations to subsequent appliance patents owned by leading companies in this technology. Looking in the opposite direction, it also identifies individual appliance patents owned by leading companies that have citation links to earlier BTO-funded research.

Table 5-1 shows the BTO-funded appliance patent families linked via citations to the largest number of subsequent patent families owned by leading companies in this technology. This table is headed by an MIT patent family filed in 1989 (with representative patent[17] US #5,032,439). It describes vacuum panels, one application of which is in refrigerators. This MIT patent family is linked via citations to 17 subsequent patent families assigned to the leading companies, specifically Bosch, Haier and Whirlpool. The latter in particular has a number of patent families related to insulated panels and doors for refrigerators that are linked to this MIT family. Lockheed Martin has a number of patent families in Table 5-1, through its management of Oak Ridge National Laboratory. These include patent families for microwave materials processing (e.g. representative patent US #5,521,360) that are linked via citations to subsequent patents for microwave ovens assigned to LG Electronics, Panasonic, Samsung and Whirlpool.

Table 5-1 – BTO-Funded Appliance Patent Families Linked via Citations to Most Subsequent Leading Company Appliance Patent Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
23576817	5032439	1989	17	MIT	Thermal insulations using vacuum panels
23184715	5521360	1994	16	Lockheed Martin (ORNL)	Apparatus and method for microwave processing of materials
25078844	4683154	1985	16	US Dept Energy	Laser sealed vacuum insulation window
45971752	8572862	2010	13	Battelle Mem Inst (PNNL)	Open-loop heat-recovery dryer
25155804	5321222	1991	12	Lockheed Martin (ORNL)	Variable frequency microwave furnace system
25107219	4107935	1977	10	US Dept Energy	High temperature refrigerator
22418957	5357756	1993	9	Lockheed Martin (ORNL)	Bipolar pulse field for magnetic refrigeration
25129462	6584784	1999	9	MRIGlobal (NREL)	Combined refrigeration system with a liquid pre-cooling heat exchanger
33540664	7076959	2003	9	Brookhaven Sci Assoc (BNL)	Enhanced magnetocaloric effect material
34837496	7148777	2004	9	Astronautics Corp	Permanent magnet assembly

Table 5-2 looks in the opposite direction to Table 5-1, and lists the appliance patent families owned by leading companies that are linked via citations to the largest number of earlier patent families funded by BTO. This table is headed by three patent families assigned to Haier (see for example representative patent US #9,797,630), all related to heat pumps that can be used in

[17] The representative patent is a single patent from a family, but it is not necessarily the priority filing.

refrigerators. These Haier patent families are each linked via citations to eight earlier BTO-funded patents, notably early patents assigned to DOE for heat pumps and magnetic refrigeration. Table 5-2 also contains two patent families assigned to Whirlpool for vacuum insulation (e.g. representative patent US #9,599,392) that are linked to four earlier BTO-funded patent families, including the MIT patent family at the head of Table 5-1.

Table 5-2 - Leading Company Appliance Patent Families Linked via Citations to Largest Number of BTO Funded Appliance Patent Families

Patent Family #	Representative Patent #	Priority Year	# BTO Fams	Assignee	Title
54835860	9797630	2014	8	Haier Group	Heat pump with restorative operation for magneto caloric material
60934992	9869493	2016	8	Haier Group	Linearly-actuated magnetocaloric heat pump
56621977	9631843	2015	8	Haier Group	Magnetic device for magneto caloric heat pump regenerator
52669399	9599392	2014	4	Whirlpool Corp.	Folding approach to create a 3D vacuum insulated door from 2D flat vacuum insulation panels
49233043	9835369	2015	4	Whirlpool Corp.	Vacuum insulated structure tubular cabinet construction
43428993	9398646	2009	3	Panasonic Corporation	Microwave heating device and microwave heating control method

We also identified high-impact appliance patents owned by leading companies that have citation links back to BTO-funded patents.[18] The idea is to highlight important technologies owned by leading companies that are linked to earlier appliance research funded by BTO. Table 5-3 lists leading company patents that are linked via citations to BTO-funded patents, and in turn have been cited as prior art by at least ten subsequent patents, resulting in a Citation Index value above two (i.e. they have each been cited at least twice as many times as expected given their age and technology).

Table 5-3 is headed by two Electrolux patents issued in 2016 (US #9,249,538 and US #9,372,031) describing laundry dryers incorporating heat pumps. These patents have been cited as prior art by 13 and 12 subsequent patents respectively, more than ten times as many citations as expected, given their recent issue dates and technology. In turn, these Electrolux patents are

[18] High-impact patents are identified using 1790's Citation Index metric. This metric is derived by first counting the number of times a patent is cited as prior art by subsequent patents. This number is then divided by the mean number of citations received by peer patents from the same issue year and technology (as defined by their first listed Cooperative Patent Classification). For example, the number of citations received by a 2010 patent in CPC F25D 11/02 (Domestic Refrigerators) is divided by the mean number of citations received by all patents in that CPC issued in 2010. The expected Citation Index for an individual patent is one. The extent to which a patent's Citation Index is greater or less than one reveals whether it has been cited more or less frequently than expected, and by how much. For example, a Citation Index of 1.5 shows that a patent has been cited 50% more frequently than expected. Meanwhile a Citation Index of 0.7 reveals that a patent has been cited 30% less frequently than expected. By extension, the expected Citation Index for a portfolio of patents is also one, with values above one showing that a portfolio has been cited more than expected, and values below one showing that a portfolio has not been cited as frequently as expected. Note that the Citation Index is calculated for U.S. patents only, due to the differences in citation practices across different countries' patent systems.

linked via citations to an earlier BTO-funded patent family related to dryer technology (representative patent US #8,572,862) assigned to Battelle Memorial Institute, through its management of Pacific Northwest National Laboratory. Whirlpool also has a number of patents in Table 5-3, including a 2015 patent (US #8,944,541) linked to the BTO-funded MIT patent highlighted above, and a much older 1992 patent (US #5,082,335), linked via citations to an early patent assigned to DOE for vacuum insulation glass windows (US #4,683,154).

Table 5-3 - Highly Cited Leading Company Appliance Patents Linked via Citations to Earlier BTO-funded Appliance Patents

Patent	Issue Year	# Cites Received	Citation Index	Assignee	Title
9249538	2016	13	12.46	Electrolux	Laundry treatment apparatus with heat pump
9372031	2016	12	10.64	Electrolux	Appliance for drying laundry
8944541	2015	18	5.26	Whirlpool	Vacuum panel cabinet structure for a refrigerator
5082335	1992	92	4.85	Whirlpool	Vacuum insulation system for insulating refrigeration cabinets
8899068	2014	15	3.77	LG Electronics	Refrigerator comprising vacuum space
7296422	2007	32	3.17	Whirlpool	Produce preservation system
6680467	2004	33	2.50	Whirlpool	Microwave delivery system with multiple magnetrons for a cooking appliance

While the patent-level results focus on BTO-funded appliance patent families, we also identified Other DOE-funded appliance families linked to subsequent patent families owned by leading companies in this technology. These Other DOE-funded families are listed in Table 5-4. There are four patent families in this table, three of which are assigned to Iowa State University, through its management of Ames National Laboratory. These families (e.g. representative patent US #5,743,095) describe magnetic refrigerant materials. They are linked to a number of subsequent patent families assigned to Haier describing magnetocaloric materials for refrigeration. The other patent family in Table 5-4 (representative patent US #4,688,399) is assigned to Carrier and describes a heat pipe array. It is linked to a subsequent Bosch family for a dishwasher containing a heat tube.

Table 5-4 - Other DOE-Funded Appliance Patent Families Linked via Citations to Subsequent Leading Company Appliance Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
25029004	5743095	1996	9	Iowa State Univ (Ames)	Active magnetic refrigerants based on Gd-Si-Ge material and refrigeration apparatus and process
46282232	7114340	2000	7	Iowa State Univ (Ames)	Method of making active magnetic refrigerant materials based on Gd-Si-Ge alloys
26883327	6589366	2000	2	Iowa State Univ (Ames)	Method of making active magnetic refrigerant, colossal magnetostriction and giant magnetoresistive materials
27099912	4688399	1984	1	Carrier Corp	Heat pipe array heat exchanger

Overall, the backward tracing element of the analysis suggests that BTO-funded and Other DOE-funded appliance patents have a different primary technological focus to the leading appliance companies. Specifically, DOE-funded patents concentrate primarily on refrigeration, while the

leading companies have a greater focus on washers and dryers. That said, it is still possible to trace the influence of DOE-funded (and particularly BTO-funded) appliance research on the leading companies, especially in refrigeration and heat exchange technologies.

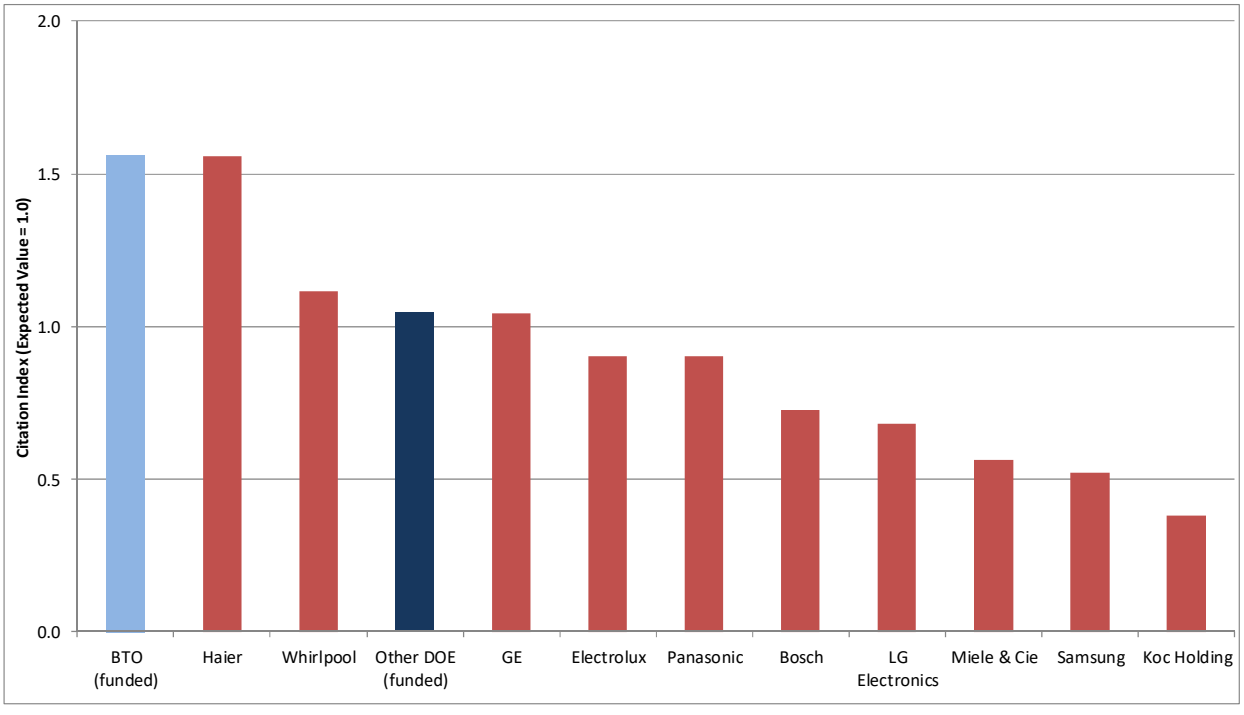
Tracing Forwards from DOE-funded Appliance Patents

The previous section of the report examines the influence of DOE-funded appliance research on technological developments associated with leading appliance companies. That analysis was based on tracing backwards from the patents of leading companies to previous generations of research. This section reports the results of an analysis tracing in the opposite direction – starting with BTO-funded (and Other DOE-funded) appliance patents, and tracing forwards in time through two generations of citations. Hence, while the previous section of the report focuses on DOE's influence upon a specific patent set (i.e. patents owned by leading appliance companies), this section of the report focuses on the broader influence of BTO-funded (and Other DOE-funded) appliance research, both within and beyond the appliance industry. Also, in order to avoid repeating earlier results, the forward tracing concentrates primarily on patents that are linked to DOE-funded appliance research, but are not owned by leading appliance companies.

Organizational Level Results

We first generated Citation Index values for the portfolios of BTO-funded and Other DOE-funded appliance patents. We then compared these Citation Indexes against those of the leading appliance companies. The results are shown in Figure 5-17.

Figure 5-17 - Citation Index for Leading Companies' Appliance Patents, plus BTO-funded and Other DOE-funded Appliance Patents



This figure reveals that BTO-funded appliance patents have a higher average Citation Index than the patents assigned to each of the leading appliance companies. Their Citation Index of 1.56 shows that they have been cited 56% more frequently than expected, given their age and technology distribution. Other DOE-funded appliance patents have a lower average Citation Index of 1.05, but this still means they have been cited slightly more frequently than expected. This Citation Index puts Other DOE-funded patents fourth among the leading companies. When evaluated alongside the findings from the backward tracing element of the analysis, Figure 5-17 suggests that DOE-funded (and especially BTO-funded) appliance patents have been relatively influential, but much of this influence has been on innovations not associated with the leading appliance companies.

The Citation Index metric measures the overall influence of DOE-funded appliance patents, but does not necessarily address the breadth of this influence across technologies. We therefore identified the Cooperative Patent Classifications (CPCs) of the patent families linked via citations to earlier BTO-funded (and Other DOE-funded) appliance patent families.[19] These CPCs reflect the influence of DOE-funded research across technologies.

Figure 5-18 - Number of Patent Families Linked via Citations to Earlier BTO-Funded Appliance Patents by CPC (Dark Green = Appliances; Light Green = Other)

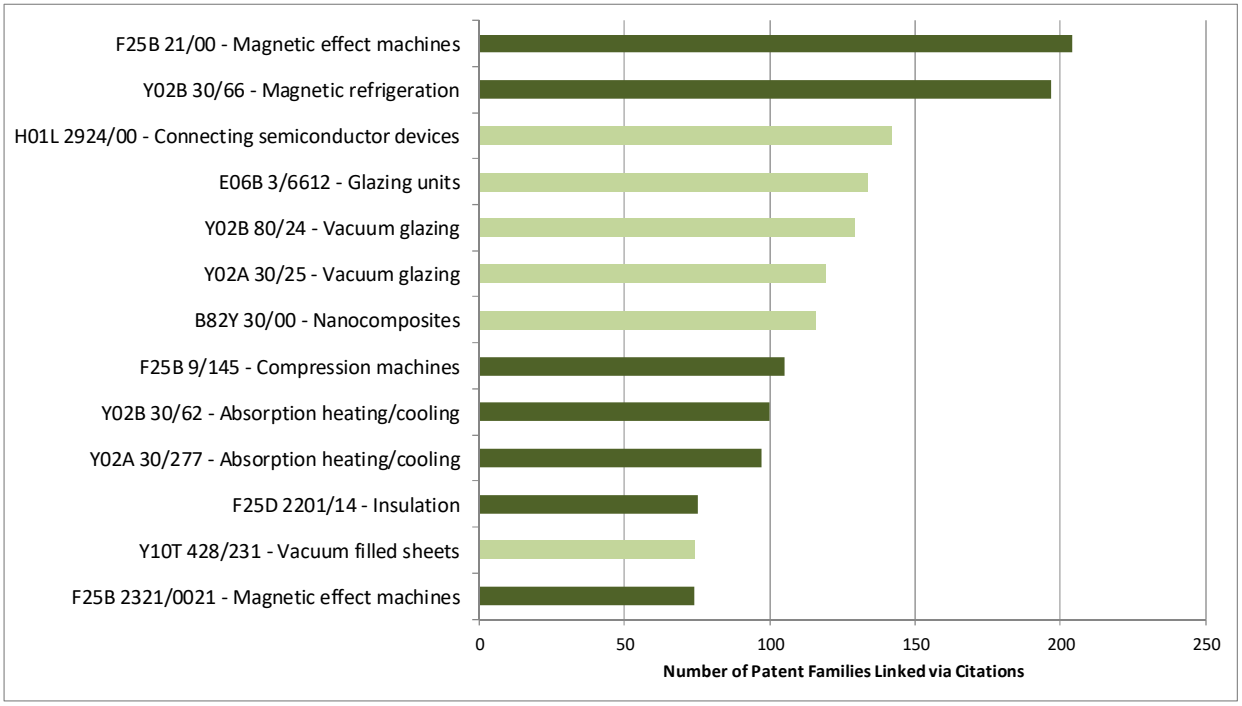


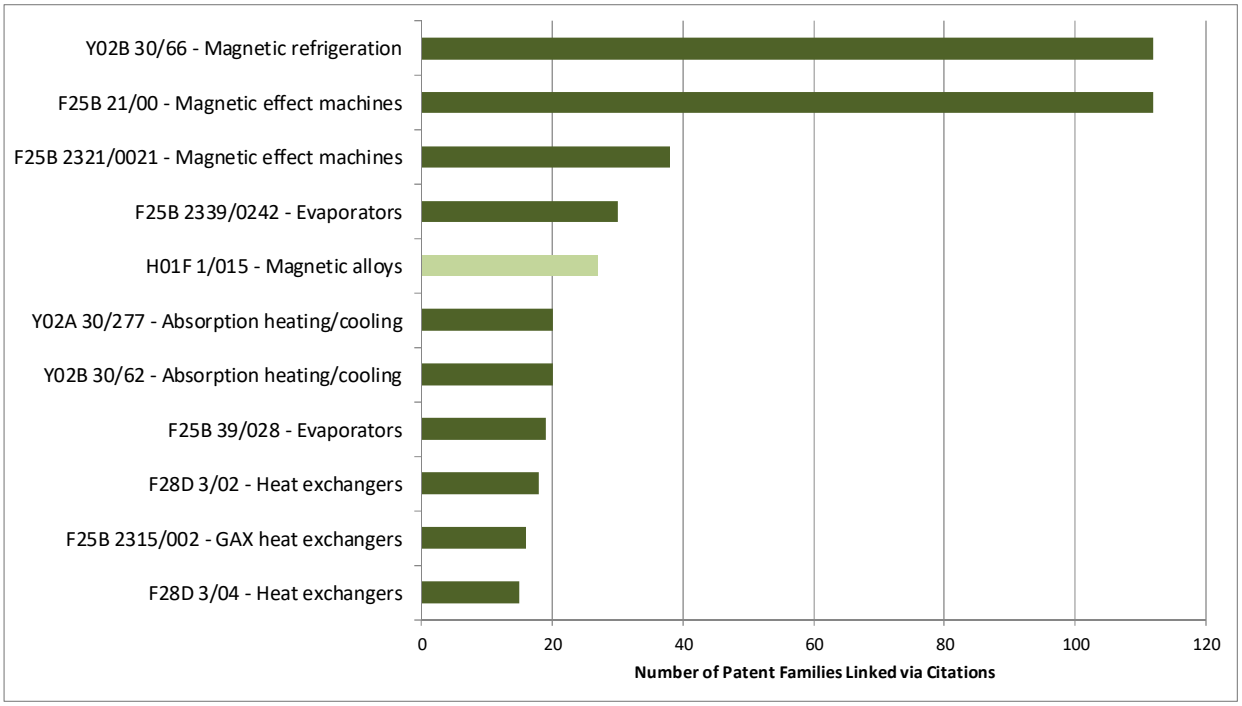
Figure 5-18 shows the CPCs with the largest number of patent families linked via citations to BTO-funded appliance patents. The CPCs in this figure are shown in two different colors – i.e. dark green for CPCs related to appliances and light green for CPCs beyond appliances. The two CPCs at the head of this figure (F25B 21/00 and Y02B 30/66) are related to magnetic

[19] Patents typically have numerous CPCs attached to them, reflecting different aspects of the invention they describe. In this analysis, we include all CPCs attached to the patents linked to earlier DOE-funded appliance patent families.

refrigeration, and are defined as within appliance technology. Other appliances-related CPCs in Figure 5-18 are concerned with absorption heating and cooling (Y02A 30/277 and Y02B 30/62) and refrigeration compressors (F25B 9/145). Figure 5-18 also features a number of CPCs related to technologies beyond appliances. CPCs related to glass-making technology (e.g. E06B 3/6612, Y02B 80/24) are particularly prominent, while there are also CPCs concerned with semiconductors (H01L 2924/00) and nanomaterials (B82Y 30/00). These are examples of the influence of BTO-funded appliance research extending into other technologies.

Figure 5-19 is similar to Figure 5-18, but is based on patent families linked via citations to Other DOE-funded appliance patents. Again, CPCs related to appliances are shown in dark green, while CPCs related to other technologies are in light green. This figure is dominated by CPCs related to appliances, with a particular focus on magnetic refrigeration (CPCs F25B 21/00 and Y02B 30/66). The only non-appliances CPC in Figure 5-19 (H01F 1/1015) is concerned with magnetic alloys, which can be used in magnetic refrigeration applications.

Figure 5-19 - Number of Patent Families Linked via Citations to Earlier Other DOE-Funded Appliance Patents by CPC



The organizations with the largest number of patent families linked via citations to earlier BTO-funded appliance patents are shown in Figure 5-20. To avoid repeating the results from earlier, this figure excludes the ten leading appliance companies used in the backward tracing element of the analysis. Also, note that Figure 5-20 includes all patent families assigned to these organizations, not just their patent families describing appliance technology. This figure is dominated by very large companies. It is headed by Koch Industries, which has 251 patent families linked via citations to earlier BTO-funded appliance patents. Many of these Koch patents families are related to glass panels and windows, as are the patent families assigned to Corning and Nippon Sheet Glass in Figure 5-20. This explains the prominence of CPCs for

glass-making technologies reported earlier in Figure 5-18. Other companies in Figure 5-20 include multinationals such as Shell, AT&T and United Technologies, and specialist appliance companies such as iRobot.

Figure 5-20 - Organizations with Largest Number of Patent Families Linked via Citations to BTO-funded Appliance Patents (excluding leading appliance companies)

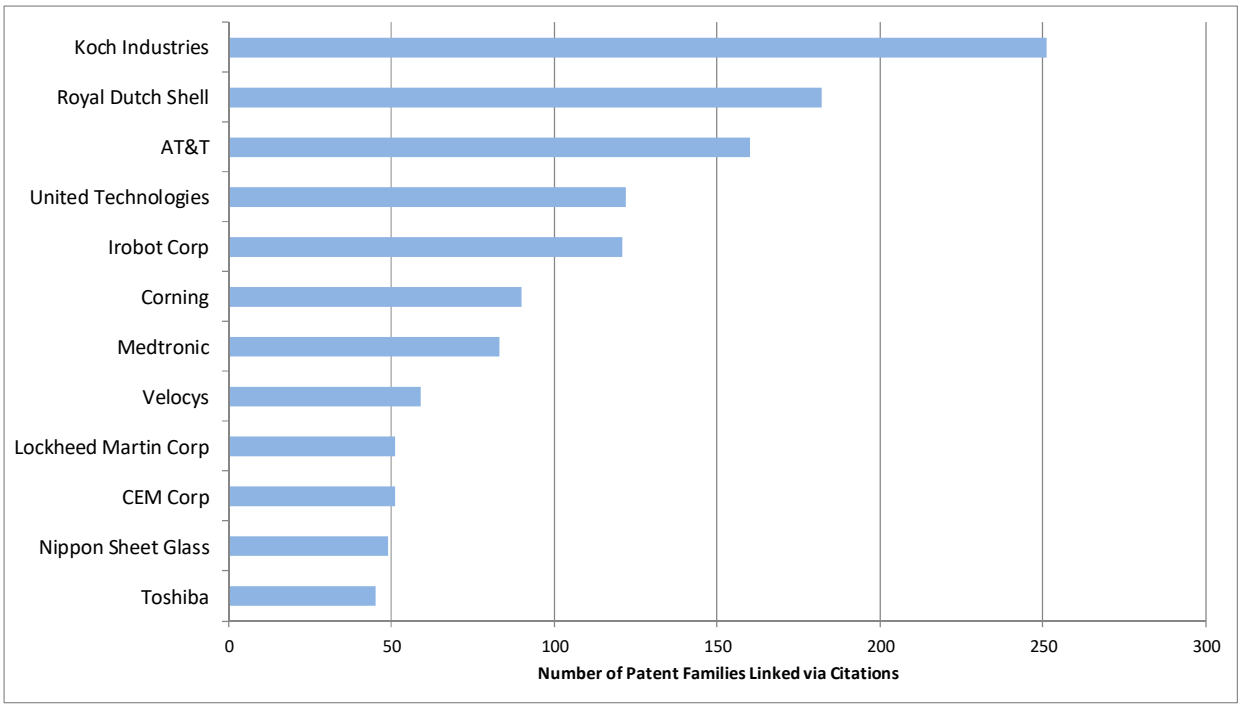


Figure 5-21 - Organizations with Largest Number of Patent Families Linked via Citations to Other DOE-funded Appliance Patents (excluding leading appliance companies)

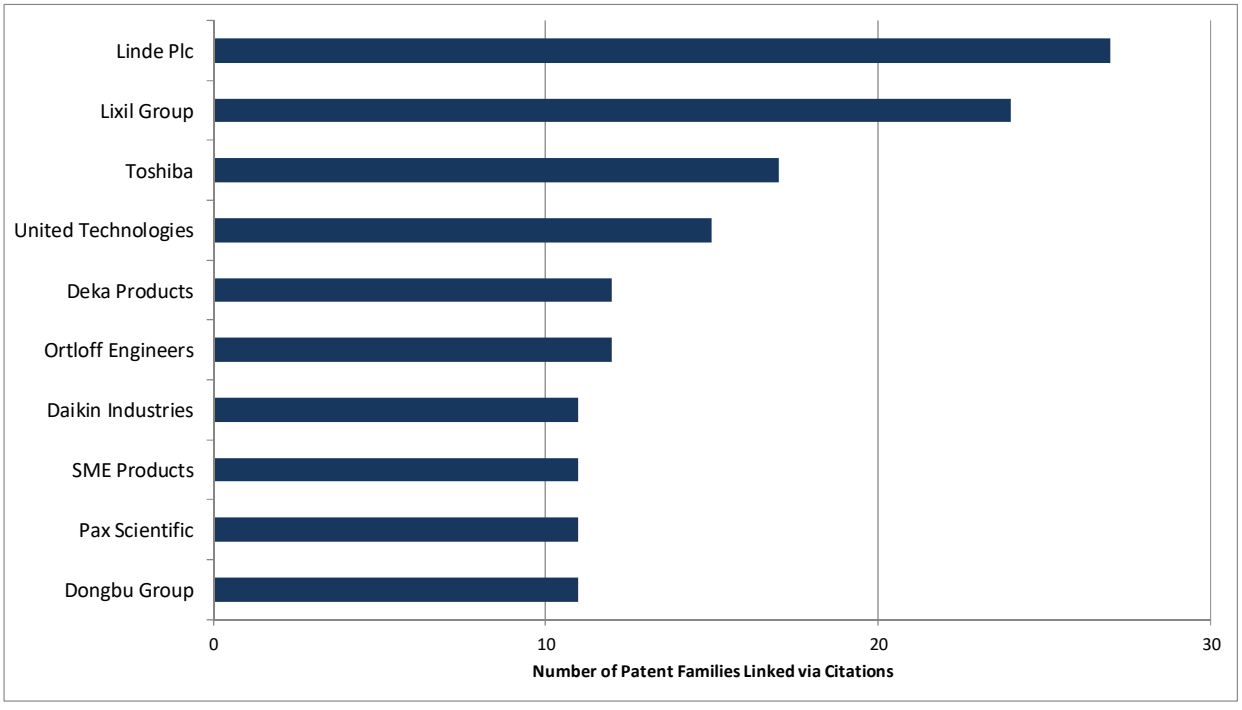


Figure 5-21 shows the organizations with the largest number of patent families linked via citations to earlier Other DOE-funded appliance patents. This figure is headed by Linde Plc with 27 patent families, many of them concerned with cryogenic technology and magnetic refrigeration. Lixil Group is in second place with 24 patent families, many concerned with refrigeration evaporators and owned by Lixil through its ownership of American Standard. The remaining companies in Figure 5-21 include large multinationals such as Toshiba and United Technologies and specialist companies including Deka and Ortloff Engineers (recently acquired by Honeywell).

Patent Level Results

This section of the report drills down to identify individual DOE-funded (and particularly BTO-funded) appliance patents whose influence on subsequent technological developments has been particularly strong. It also highlights patents that have extensive citation links to earlier BTO-funded appliance research.

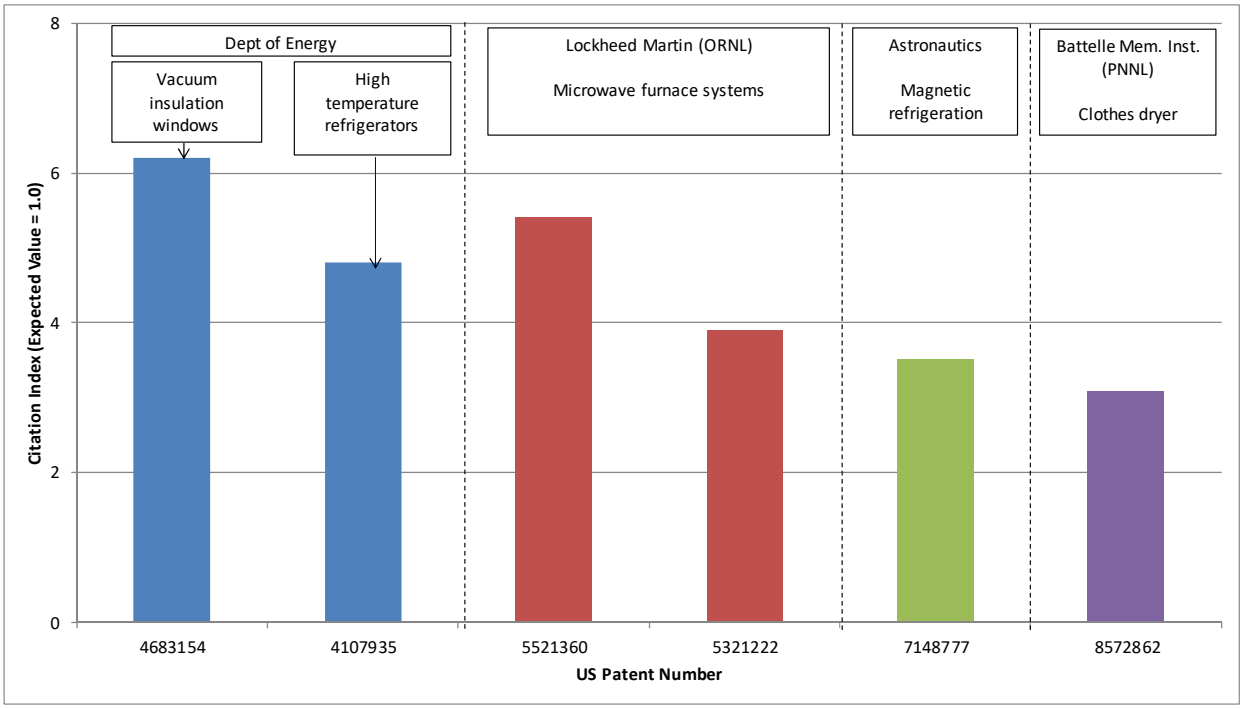
The simplest way of identifying high-impact BTO-funded appliance patents is via overall Citation Indexes. The BTO-funded patents with the highest Citation Index values are shown in Table 5-5, with selected patents also presented in Figure 5-22. The patents in this table include older patents that have 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 peer patents of the same age and technology.

Table 5-5 – List of Highly Cited BTO-Funded Appliance Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
4683154	1987	141	6.20	US Dept Energy	Laser sealed vacuum insulation window
5521360	1996	105	5.41	Lockheed Martin (ORNL)	Apparatus and method for microwave processing of materials
4107935	1978	82	4.80	US Dept Energy	High temperature refrigerator
4332135	1982	79	4.03	US Dept Energy	Active magnetic regenerator
5321222	1994	84	3.90	Lockheed Martin (ORNL)	Variable frequency microwave furnace system
7148777	2006	37	3.51	Astronautics Corp	Permanent magnet assembly
5270092	1993	70	3.17	Univ California (LBNL)	Gas filled panel insulation
8572862	2013	13	3.08	Battelle Mem Inst (PNNL)	Open-loop heat-recovery dryer
4398398	1983	52	3.04	Univ California (LANL)	Acoustical heat pumping engine

The patent at the head of Table 5-5 (US #4,683,154) is assigned to DOE, and describes thermal glass panes. Since it was issued in 1987, this patent has been cited as prior art by 141 subsequent patents, which is more than six times as many citations as expected for a patent of its age and technology. The patent in second place (US #5,521,360) is a 1996 Lockheed Martin (Oak Ridge National Laboratory) patent describing microwave furnace technology. This patent (which was highlighted earlier in the backward tracing element of the analysis) has been cited by 105 subsequent patents, more than five times as many citations as expected. More recent patents in Table 5-5 include a 2006 Astronautics patent (US #7,148,777) describing magnetic refrigeration, and a 2013 Pacific Northwest National Laboratory patent (US #8,572,862) for a clothes dryer.

Figure 5-22 – Examples of Highly-Cited BTO-funded Appliance Patents



The Citation Indexes in Table 5-5 are based on a single generation of citations to BTO-funded appliance patents. Tables 5-6 and 5-7 extend this by examining a second generation of citations – i.e. they show the BTO-funded appliance patents linked via citations to the largest number of subsequent patent families.[20] These subsequent families are divided into two groups, according to whether they are within or beyond appliance technology (i.e. whether they are in the appliance patent universe constructed in the initial step of this project). This provides insights into which BTO-funded patent families have been particularly influential within appliance technology, and which have had a broader impact beyond appliances.

Table 5-6 contains older patent families, with priority dates prior to 1999. This table is headed by a DOE patent family describing thermal glass panes. This family contains the patent (US #4,683,154) highlighted above among the highly-cited patents in Table 5-5. It is linked via citations to 888 subsequent patent families, only 22 of which are within appliances, with many of the remaining families related to glass-making technology. The second and third patent families in Table 5-6 are assigned to Lockheed Martin, through its management of Oak Ridge National Laboratory. These patent families again contain patents highlighted in Table 5-5, plus in the backward tracing element of the analysis (e.g. US #5,521,360). One feature of all of the patent families in Table 5-6 is that they are linked via citations primarily to subsequent patents outside appliance technology.

[20] The BTO-funded patent families are divided into two tables based on their age, since older patents tend to be connected to larger numbers of subsequent patents, simply because there has been more time for them to become linked to future generations of technology.

Table 5-6 – Pre-1999 BTO-funded Appliance Patent Families Linked via Citations to Largest Number of Subsequent Appliance/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Appliance Fams	Assignee	Title
25078844	1985	4683154	888	22	US Dept Energy	Laser sealed vacuum insulation window
23184715	1994	5521360	662	72	Lockheed Martin (ORNL)	Apparatus and method for microwave processing of materials
25155804	1991	5321222	509	81	Lockheed Martin (ORNL)	Variable frequency microwave furnace system
22858742	1981	4332135	448	12	US Dept Energy	Active magnetic regenerator
25107219	1977	4107935	387	19	US Dept Energy	High temperature refrigerator
23959999	1990	5174130	372	1	Sonic Compressor Systems	Refrigeration system having standing wave compressor
23576817	1989	5032439	359	29	MIT	Thermal insulations using vacuum panels
24984849	1991	5270092	334	2	Univ California (LBNL)	Gas filled panel insulation
24486279	1996	5689966	273	0	Battelle Mem Inst (PNNL)	Method and apparatus for desuperheating refrigerant
24281025	1995	5636520	178	9	Spauschus Associates	Method of removing an immiscible lubricant from an refrigeration system

Table 5-7 contains newer BTO-funded patent families, with priority dates from 1999 onwards. That said, most of these families are still relatively old, dating from around the start of this century. The table is headed by a patent family (representative patent US #6,222,170) assigned to UT-Battelle, through its management of Oak Ridge National Laboratory. This family describes microwave technology, and is linked via citations to 138 subsequent patent families, fifteen of which are related to appliance technology. The patent family in second place is assigned to Astronautics, and contains the highly-cited patent (US #7,148,777) highlighted earlier in Table 5-5. This family describes magnetic refrigeration, and is linked to 93 subsequent patent families, only nine of which are related to appliances. In general, the BTO-funded patent families in Table 5-7 are again linked via citations to larger numbers of families from outside appliance technology than from within this technology. Exceptions to this include the two patent families at the bottom of the table, one of which is related to clothes dryers and the other to refrigeration.

Table 5-7 – Post-1998 BTO-funded Appliance Patent Families Linked via Citations to Citations to Largest Number of Subsequent Appliance/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Appliance Fams	Assignee	Title
23508835	1999	6222170	138	15	UT-Battelle (ORNL)	Apparatus and method for microwave processing of materials using field-perturbing tool
34837496	2004	7148777	93	9	Astronautics Corp	Permanent magnet assembly
22929247	1999	6185944	63	3	MRI Global (NREL)	Refrigeration system with a compressor-pump unit and a liquid-injection desuperheating line
27398791	2000	6467282	58	3	ADA Technologies	Frost sensor for use in defrost controls for refrigeration
29250220	2002	6637211	43	0	Univ California (LANL)	Circulating heat exchangers for oscillating wave engines and refrigerators
33540664	2003	7076959	35	9	Brookhaven Sci Assoc (BNL)	Enhanced magnetocaloric effect material
23565690	1999	6250090	22	0	Lockheed Martin (ORNL)	Apparatus and method for evaporator defrosting
45971752	2010	8572862	18	18	Battelle Mem Inst (PNNL)	Open-loop heat-recovery dryer
25129462	1999	6584784	14	9	MRI Global (NREL)	Combined refrigeration system with a liquid pre-cooling heat exchanger

The tables above identify BTO-funded patent families linked particularly strongly to subsequent technological developments. Table 5-8 looks in the opposite direction, and identifies highly-cited patents linked to earlier BTO-funded appliance patents. As such, these are examples where BTO-funded appliance research has formed part of the foundation for subsequent high-impact technologies. This table focuses on patent families not owned by the leading appliance companies, since those families were examined in the backward tracing element of the analysis.

The patent at the head of Table 5-8 (US #6,228,904) is assigned to Nanomaterials Research Corporation, and describes nanoscale powders that can be used in composites and devices. This patent has been cited as prior art by 278 subsequent patents, which is almost twelve times as many citations as expected for a patent of its age and technology. The second patent in Table 5-8 (US #8,099,964) is a 2012 Toshiba patent describing magnetic refrigeration. This patent has been cited by 68 subsequent patents, more than eleven times as many citations as expected. Meanwhile, the third patent in Table 5-8 (US #6,998,776) is assigned to Corning and describes glass package fabrication. It has been cited by 167 subsequent patents, more than ten times as many as expected. The remaining patents in Table 5-8 are assigned to a number of different organizations, and cover a variety of technologies, including thermal energy storage, robot

vacuums and air purification. This reflects the influence of BTO-funded appliance patents on high-impact innovations across a range of applications.

Table 5-8 - Highly Cited Patents (not from leading appliance companies) Linked via Citations to Earlier BTO-funded Appliance Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
6228904	2001	278	11.96	Nanomaterials Research Corp	Nanostructured fillers and carriers
8099964	2012	68	11.16	Toshiba Corp	Magnetic refrigerating device and magnetic refrigerating method
6998776	2006	167	10.64	Corning Inc.	Glass package that is hermetically sealed with a frit and method of fabrication
7832207	2010	94	10.58	General Compression Inc	Systems and methods for energy storage and recovery using compressed gas
7373805	2008	75	10.34	UK Ministry of Defence	Apparatus for directing particles in a fluid
6701749	2004	93	9.93	Koch Industries Inc	Vacuum IG window unit with edge seal at least partially diffused at temper and completed via microwave curing
8234876	2012	47	9.66	Ice Energy Inc	Utility managed virtual power plant utilizing aggregated thermal energy storage
7805220	2010	163	9.58	ThreeSixty Group	Robot vacuum with internal mapping system
7837958	2010	64	9.47	S.C. Johnson & Son	Device and methods of providing air purification in combination with superficial floor cleaning
8387193	2013	45	8.44	Irobot Corp	Autonomous surface cleaning robot for wet and dry cleaning

As with the backward tracing element of the analysis, the patent-level results from the forward tracing focus on BTO-funded appliance patents. That said, within the forward tracing, we did also identify Other DOE-funded appliance patent families linked to the largest number of subsequent patent families within and beyond appliance technology. These Other DOE-funded appliance families are shown in Table 5-9.

Table 5-9 - Other DOE-funded Appliance Patent Families Linked via Citations to Largest Number of Subsequent Appliance/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Appliance Fams	Assignee	Title
25029004	1996	5743095	249	12	Iowa State Univ (Ames)	Active magnetic refrigerants based on Gd-Si-Ge material and refrigeration apparatus
27099912	1984	4688399	98	1	Carrier Corp	Heat pipe array heat exchanger
25350009	1978	4158295	71	0	Carrier Corp	Spray generators for absorption refrigeration systems
23352954	1982	4441902	63	0	Kaman Sciences Corp	Heat reclaiming method and apparatus
46282232	2000	7114340	24	7	Iowa State Univ (Ames)	Method of making active magnetic refrigerant materials based on Gd-Si-Ge alloys
26883327	2000	6589366	18	2	Iowa State Univ (Ames)	Method of making active magnetic refrigerant and giant magnetoresistive materials

The patent family at the head of Table 5-9 (representative patent #5,743,095) is assigned to the Iowa State University, through its management of Ames National Laboratory. It describes magnetic refrigeration materials, and is linked via citations to 249 subsequent patent families, only twelve of which are related to appliances. This patent family was highlighted above in the backward tracing element of the analysis (see Table 5-4). The patent families in second and third place in Table 5-9 are both assigned to Carrier Corp. The first of these Carrier families (representative patent US #4,688,399) describes a heat pipe array, and is linked via citations to 98 subsequent patent families, only one of which is within appliance technology. The second Carrier patent family (representative patent US #4,158,295) outlines an absorption refrigeration system, and is linked to 71 subsequent families, all of them outside appliance technology. In general, the pattern of citation links in Table 5-9 suggests that the influence of the Other DOE-funded appliance patent families can be seen primarily outside appliance technology.

The forward tracing element of the analysis thus shows that BTO-funded and Other DOE-funded appliance research has influenced subsequent innovations associated with a number of very large companies. This influence can be seen mainly in technologies beyond appliances, such as nanocomposites, advanced materials and energy storage.

Overall, the results from the appliances analysis suggest that DOE-funded patenting in this technology remained relatively consistent throughout the analysis period, with BTO-funded patents representing a high percentage of the total. DOE-funded patents focus primarily on refrigeration technology, while the patents of leading appliance companies have a much broader range, with a particular concentration on washers and dryers. That said, the backward tracing reveals that it is still possible to trace the influence of DOE-funded (and particularly BTO-funded) appliance research on the leading companies, especially in refrigeration and heat exchange technologies. Meanwhile, the forward tracing reveals that much of the influence of BTO-funded and Other DOE-funded appliance patents can be seen on subsequent technologies from beyond appliances, notably nanocomposites, advanced materials and energy storage.

6. Results – Water Heating

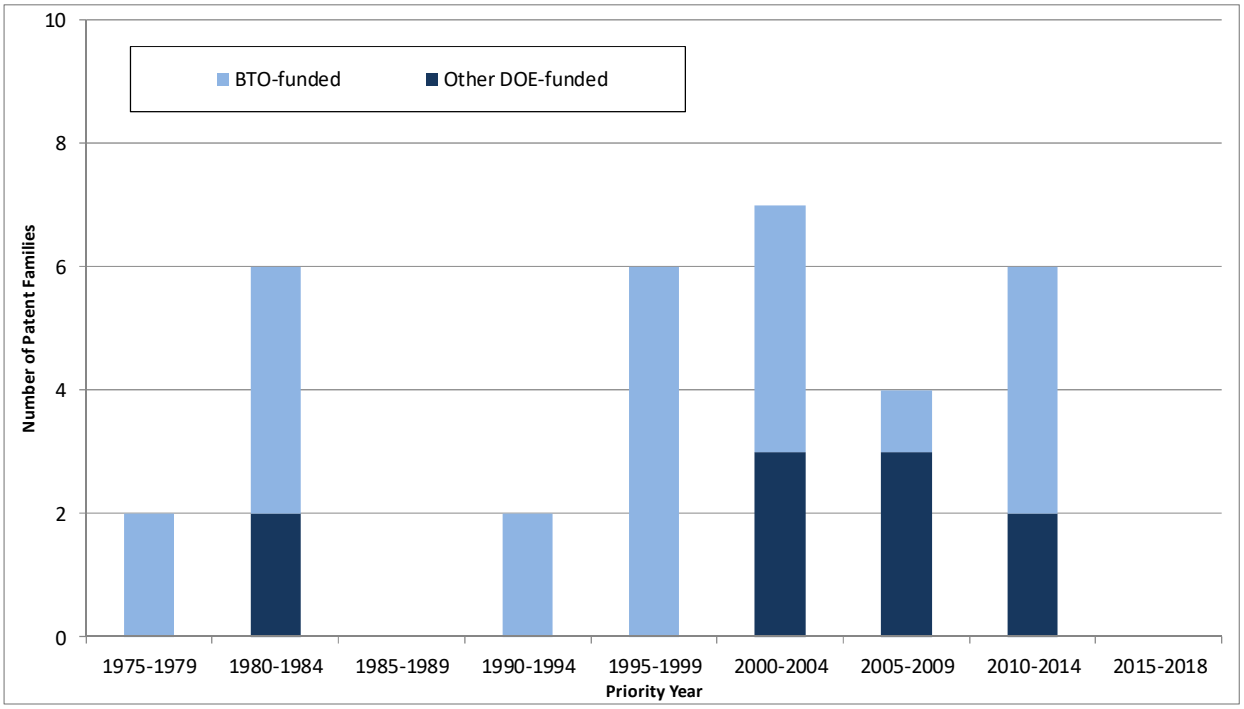
This section of the report outlines the results of our analysis tracing the influence of BTO-funded and Other DOE-funded water heating research on subsequent developments both within and beyond water heating technology. The results are divided into three main sections. In the first section, we examine trends in patenting over time in water heating, and assess the distribution of BTO-funded and Other DOE-funded patents across water heating technologies. The second section then reports the results of an analysis tracing backwards from water heating patents owned by the leading companies in this technology. The purpose of this analysis is to determine the extent to which water heating innovations developed by leading companies build upon earlier water heating research funded by BTO (plus water heating research funded by the remainder of DOE). In the third section, we report the results of an analysis tracing forwards from BTO-funded (and Other DOE-funded) water heating patents. The purpose of this analysis is to assess the broader influence of DOE-funded research upon subsequent developments within and beyond water heating technology.

Overall Trends in Water Heating Patenting

Trends in Water Heating Patenting over Time

Figure 6-1 shows the number of BTO-funded and Other DOE-funded water heating patent families by priority year – i.e. the year of the first application in each patent family. This figure reveals that DOE-funded water heating patenting was relatively sparse in each time period covered by the analysis. The most active period was between 1995 and 2014, with the peak occurring in 2000-2004, with a total of seven patent families filed in this time period (four of them BTO-funded). The least active period was between 1985 and 1994, with only two patent families filed. In total, there are 33 DOE-funded water heating patent families, 23 of them funded by BTO.

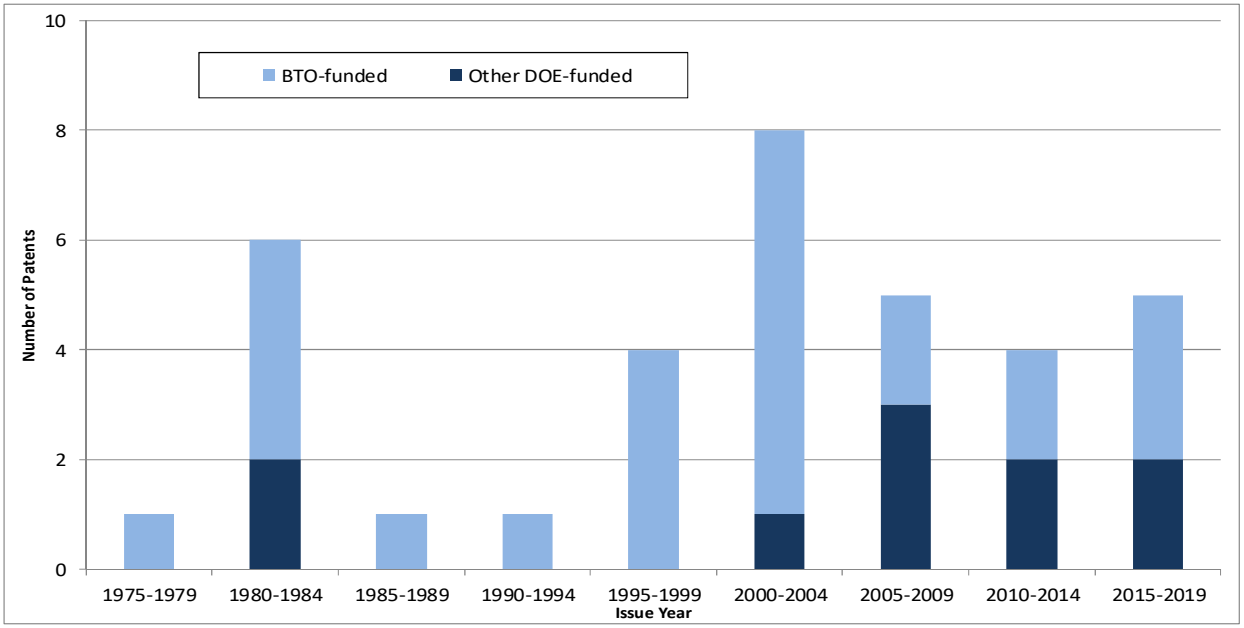
Figure 6-1 - Number of Water Heating Patent Families funded by BTO and Other DOE Sources by Priority Year (5-Year Totals)



Note: The final time period in this figure is 2015-2018, and is shown for completeness, although data for this time period are incomplete. Our primary data collection covered only patents issued through 2018. Due to time lags associated with the patenting process, only a fraction of the patent families from 2015-2018 will be included.

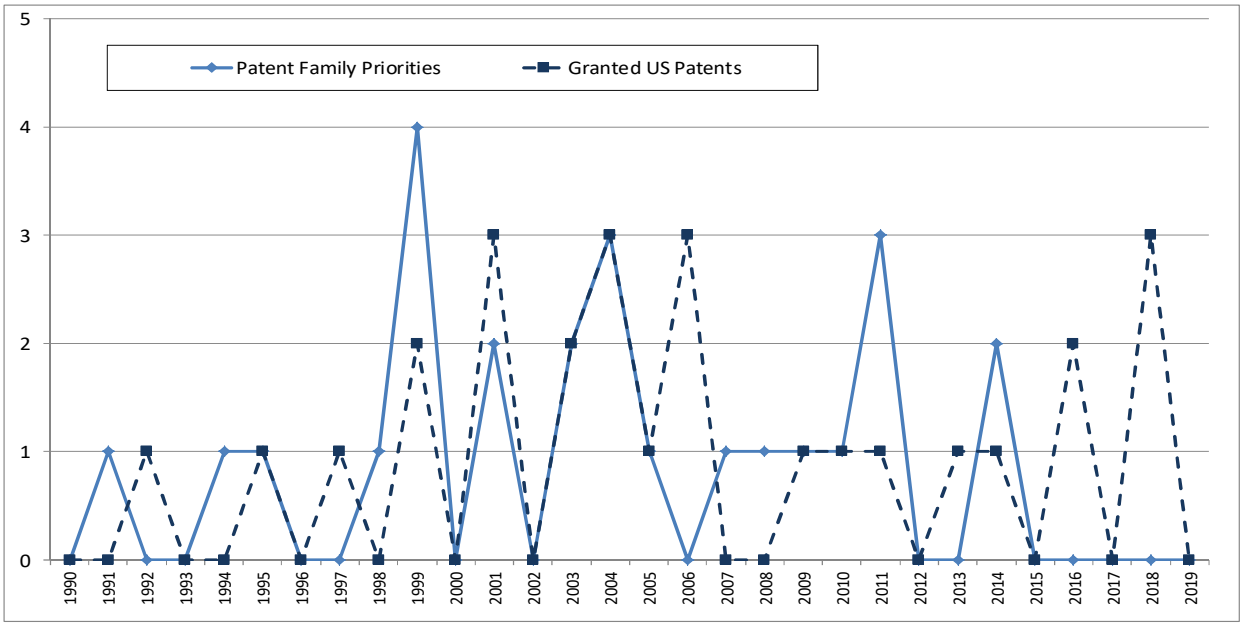
Figure 6-2 shows the number of water heating granted U.S. patents funded by DOE. This figure follows a similar pattern to Figure 6-1, with very little patent activity between 1985 and 1994, followed by a more active period from 1995 onwards. The peak was in 2000-2004, with eight DOE-funded U.S. patents granted, seven of which were funded by BTO. Overall, there are 35 DOE-funded U.S. patents, 25 of which are BTO-funded.

Figure 6-2 – No. of DOE-Funded Water Heating US Patents by Issue Year (5-Year Totals)



Note: The data collection period for this analysis ended with 2018. Any 2019 patents are included because they are members of patent families with pre-2019 patents. No new patent search for 2019 was carried out.

Figure 6-3 - Number DOE-funded Water Heating Patent Families (by Priority Year) and Granted U.S. Patents (by Issue Year)



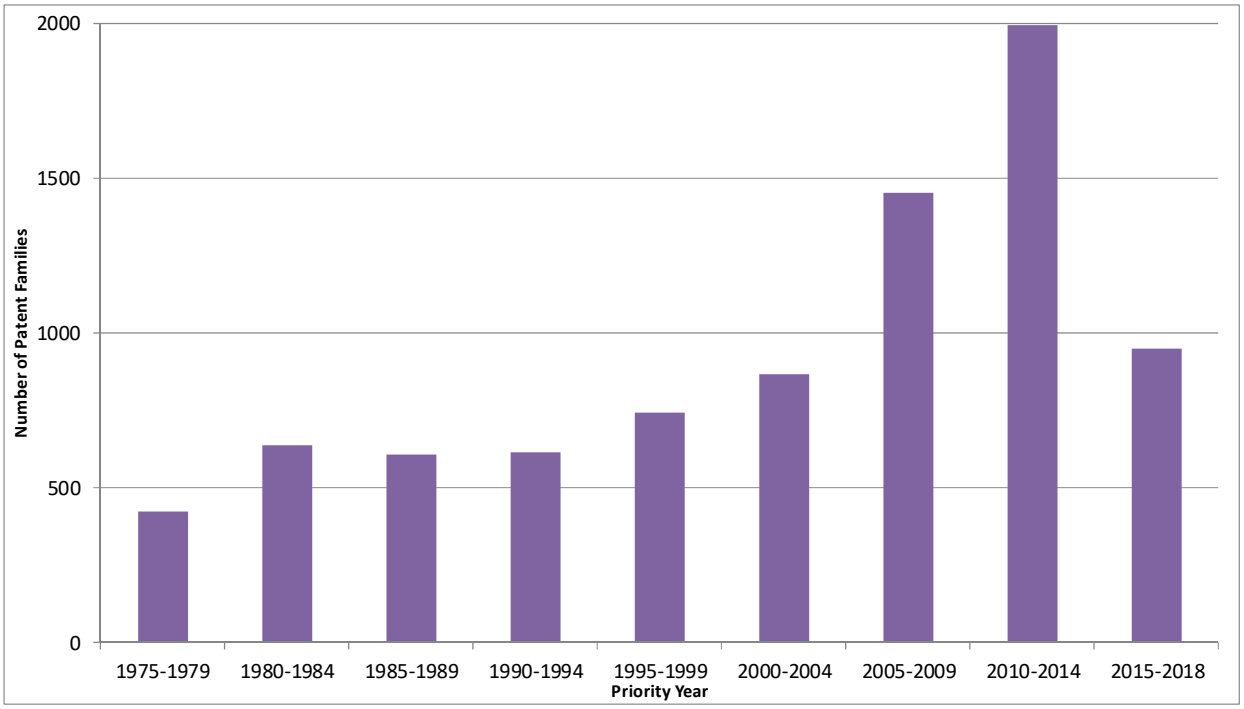
Note: The data collection period for this analysis ended with 2018. The 2019 patents are additional patents included because they are members of patent families with pre-2019 patents. No new patent search for 2019 was carried out.

Comparing Figures 6-1 and 6-2 shows the effect of time lags in the patenting process. For example, there are no patent families in the most recent time period, but there are five granted U.S. patents resulting from families filed in earlier periods. These time lags can also be seen in Figure 6-3, which shows patent family priority years alongside issue years for granted U.S. water

heating patents (BTO and Other DOE are combined in this figure, to simplify the presentation). Due to the low numbers of both patent families and granted patents, the trends in Figure 6-3 are very choppy. That said, it is possible to see how the small increases in patent families filed in 2011 and 2014 resulted in corresponding increases in granted patents in 2016 and 2018. Note that, due to the primary data collection for this analysis ending in 2018, the number granted U.S. patents declines in 2019, and the number of patent families is zero.

Figures 6-1 – 6-3 focus on DOE-funded water heating patent families. Figure 6-4 broadens the scope, and shows the overall number of water heating patent families by priority year (based on USPTO, EPO, and WIPO filings). This figure reveals a distinct trend in water heating patenting over time. Between 1980 and 1994, the overall number of water heating patent families was relatively consistent at around 120 per year (i.e. 600-650 in each 5-year period). The number of patent families then started to increase, slowly at first in 1995-1999 and 2000-2004, and then much more rapidly in 2005-2009 and 2010-2014, peaking at 1,995 filed in the latter time period. Hence, there were more than three times as many water heating patent families filed in 2010-2014 as there were in 1990-1994. The number of patent families declined to 950 in 2015-2018, although data for this time period are incomplete.

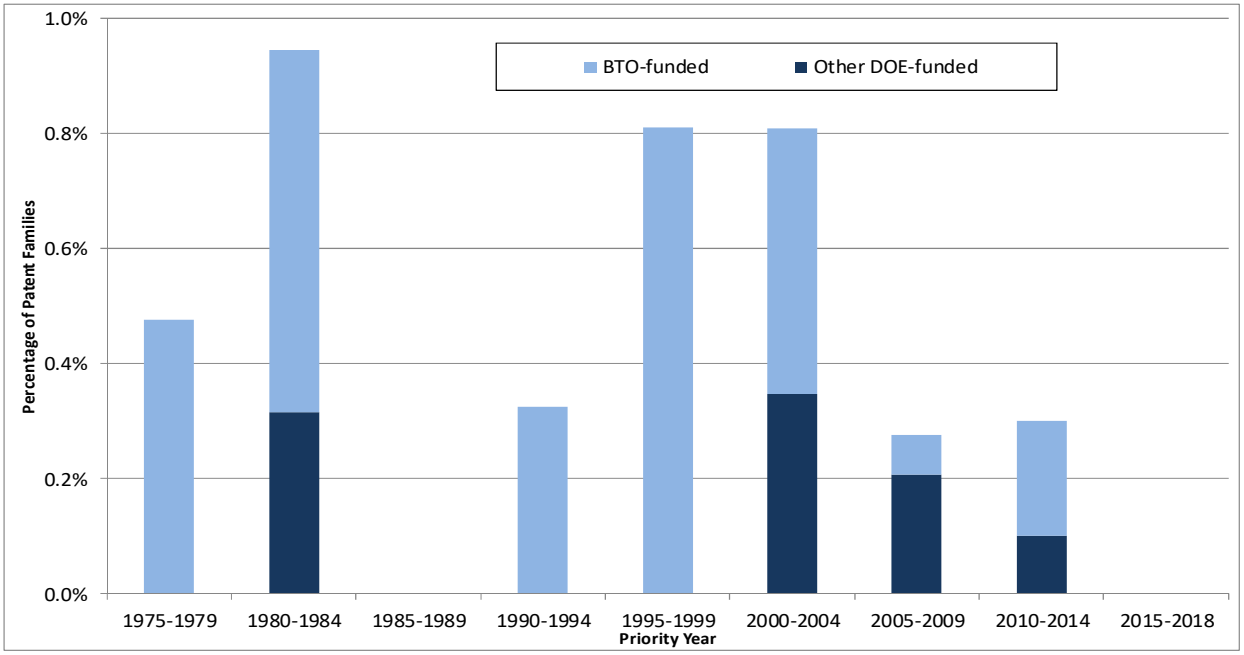
Figure 6-4 - Total No. of Water Heating Patent Families by Priority Year (5-Year Totals)



Note: The final time period in this figure is 2015-2018. Data for this time period are incomplete. Due to time lags associated with the patenting process, only a fraction of the patent families from this time period will be included.

Figure 6-5 shows the percentage of water heating patent families in each time period that were funded by DOE (BTO plus Other DOE). This figure reveals that DOE-funded patent families represented less than 1% of the total number of water heating families in each time period, peaking at 0.94% in 1980-1984. Overall, 0.4% of water heating patent families in 1976-2018 were funded by DOE. This suggests that DOE was one of many organizations involved in water heating research throughout the period covered by the analysis.

Figure 6-5- Percentage of Water Heating Patent Families Funded by DOE by Priority Year

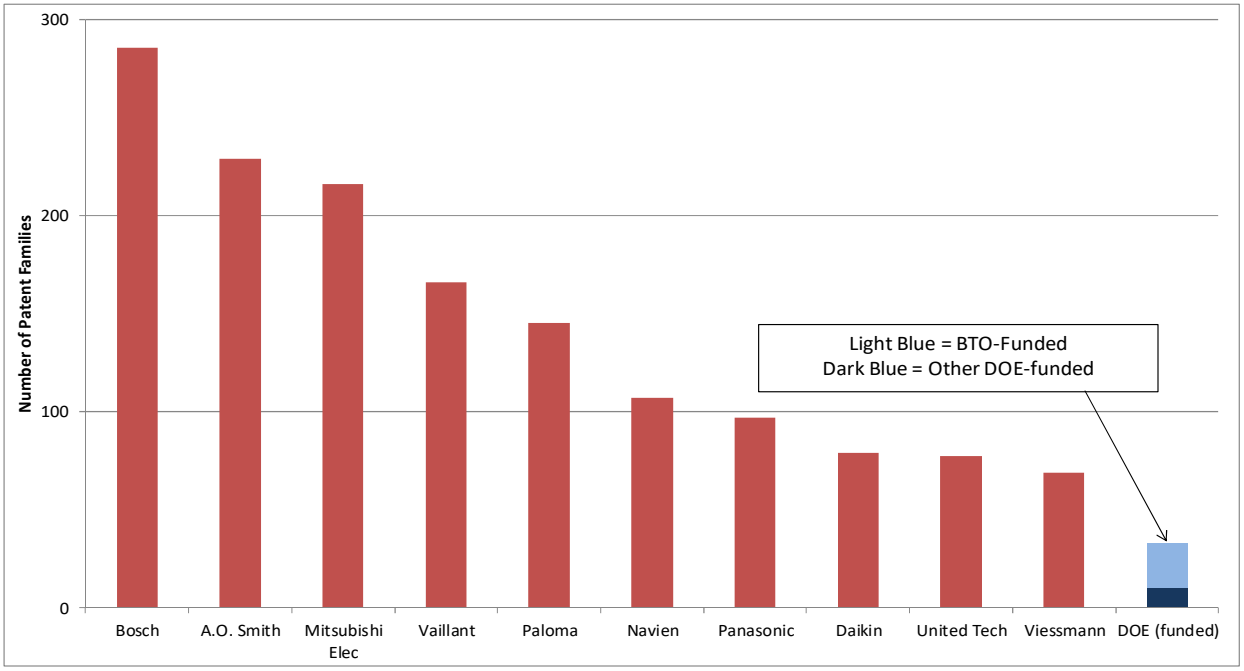


Note: The final time period in this figure is 2015-2018. Data for this time period are incomplete. Due to time lags associated with the patenting process, only a fraction of the patent families from this time period will be included.

Leading Water Heating Assignees

The ten leading patenting companies in water heating technology are listed above in Table 3-7, along with their number of water heating patent families. Figure 6-6 shows the same information in graphical form, while also including DOE-funded patent families.

Figure 6-6 – Leading Water Heating Companies (based on number of patent families)



This figure reveals that the Bosch has the largest water heating patent portfolio, containing 286 patent families, followed by A.O. Smith (229 families), Mitsubishi Electric (216) and Vaillant (166). One notable feature of Figure 6-6 is the geographical distribution of the leading companies, with five from Asia, three from Europe and two from North America. This reinforces the earlier point that, while the analysis does not include patents from Asian systems, this does not mean that patents associated with Asian companies are excluded.

The DOE-funded water heating portfolio of 33 patent families (23 BTO-funded; 10 Other-DOE funded) is much smaller than the portfolios associated with the leading appliance companies in Figure 6-6. In evaluating the influence of DOE-funded water heating patents versus the influence of patents owned by the leading companies, we therefore take this difference in portfolio size into account.

Assignees of BTO/Other DOE-funded Water Heating Patents

The DOE-funded water heating patent portfolios are constructed somewhat differently from the portfolios of the ten leading companies listed in Figure 6-6. Specifically, DOE's 33 patent families are those funded by DOE, but they are not necessarily assigned to the agency. For example, BTO (or another DOE office) may have partially or fully funded research projects at DOE labs or companies. In such cases, the assignees of any resulting patents may be the DOE lab managers or companies.

Figure 6-7 - Assignees with Largest No. of BTO-Funded Water Heating Patent Families

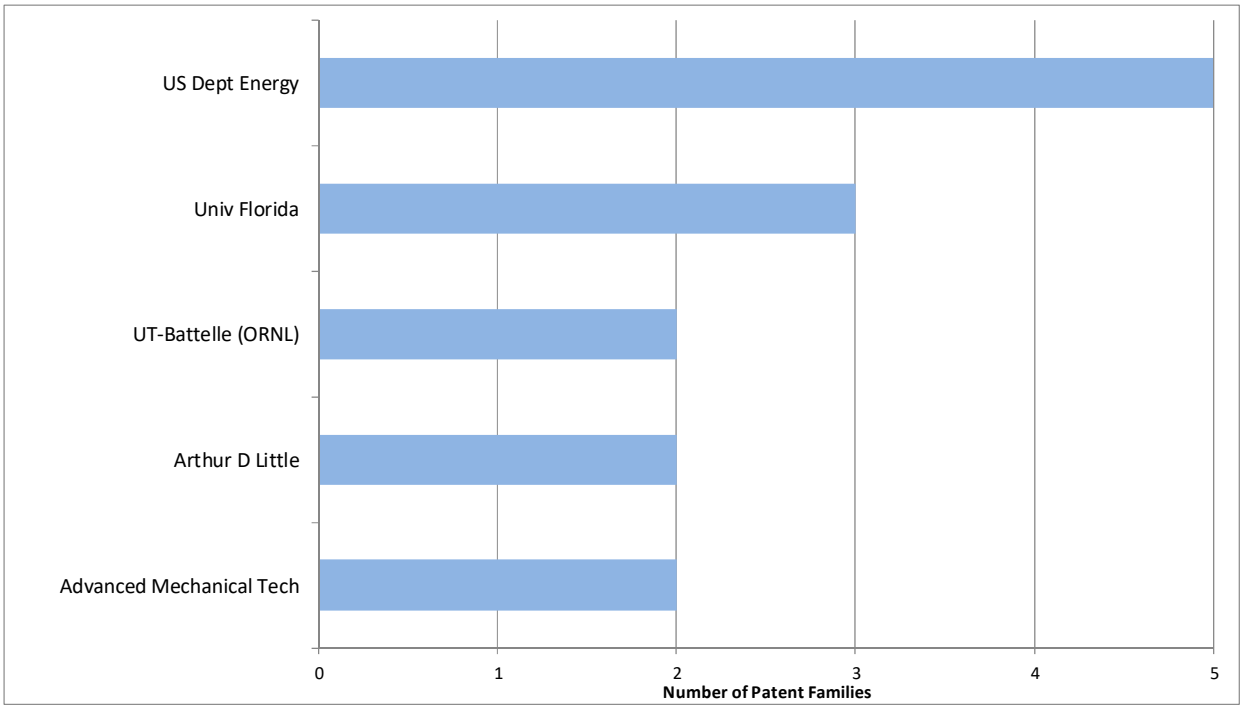
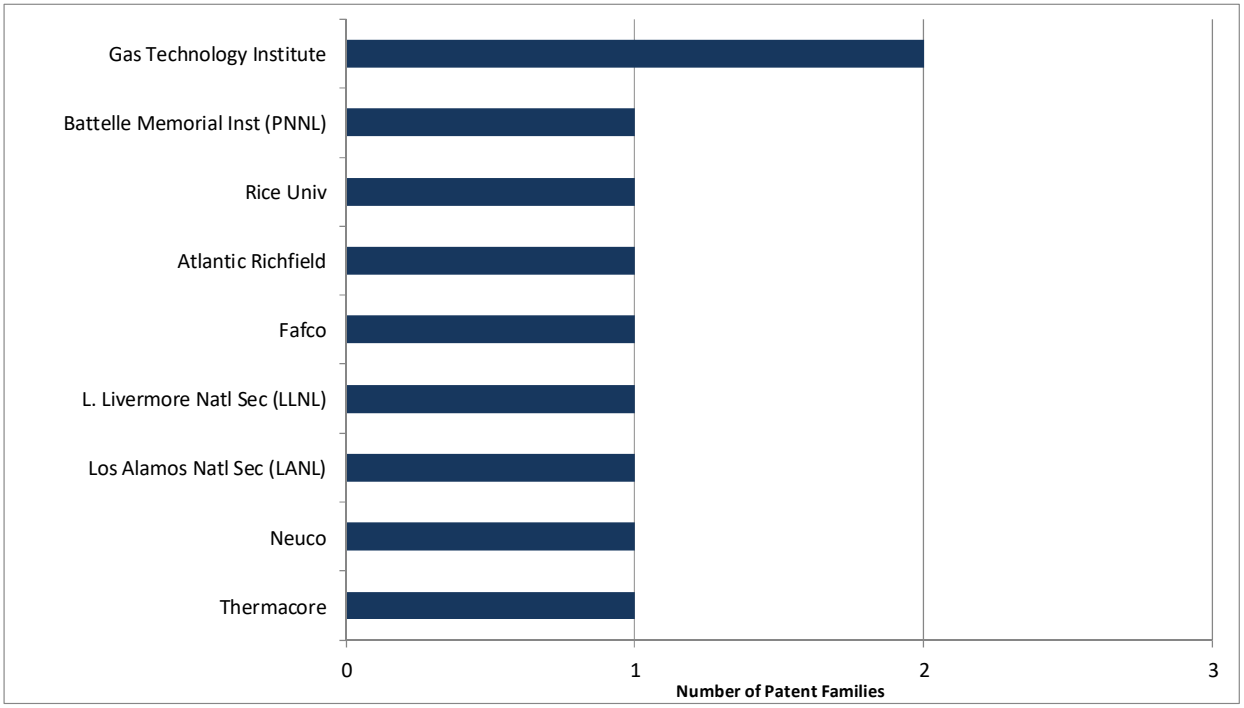


Figure 6-7 shows the leading assignees on BTO-funded water heating patent families. The assignee at the head of this figure is DOE itself, with five BTO-funded water heating patents. Such an assignment may occur for various reasons, including where the inventors are federal

employees; where the funding recipient elects not to pursue patent protection for, or take title to, the invention; or where the funding recipient does not have the right to take title to the invention. The University of Florida is in second place in Figure 6-7 with three patent families, followed by UT-Battelle (through its management of Oak Ridge National Laboratory), Arthur D. Little and Advanced Mechanical Technologies, each with two patent families.

Figure 6-8 shows the assignees on Other DOE-funded water heating patent families (since there are only ten such families in total, all assignees are shown). This figure reveals that there is only one assignee with more than one Other DOE-funded water heating patent family – Gas Technology Institute, which has two such families. The remaining assignees in Figure 6-8 have one patent family each, and include universities, companies and DOE lab managers.

Figure 6-8 - Assignees with Largest Number of Other DOE-funded Water Heating Patent Families



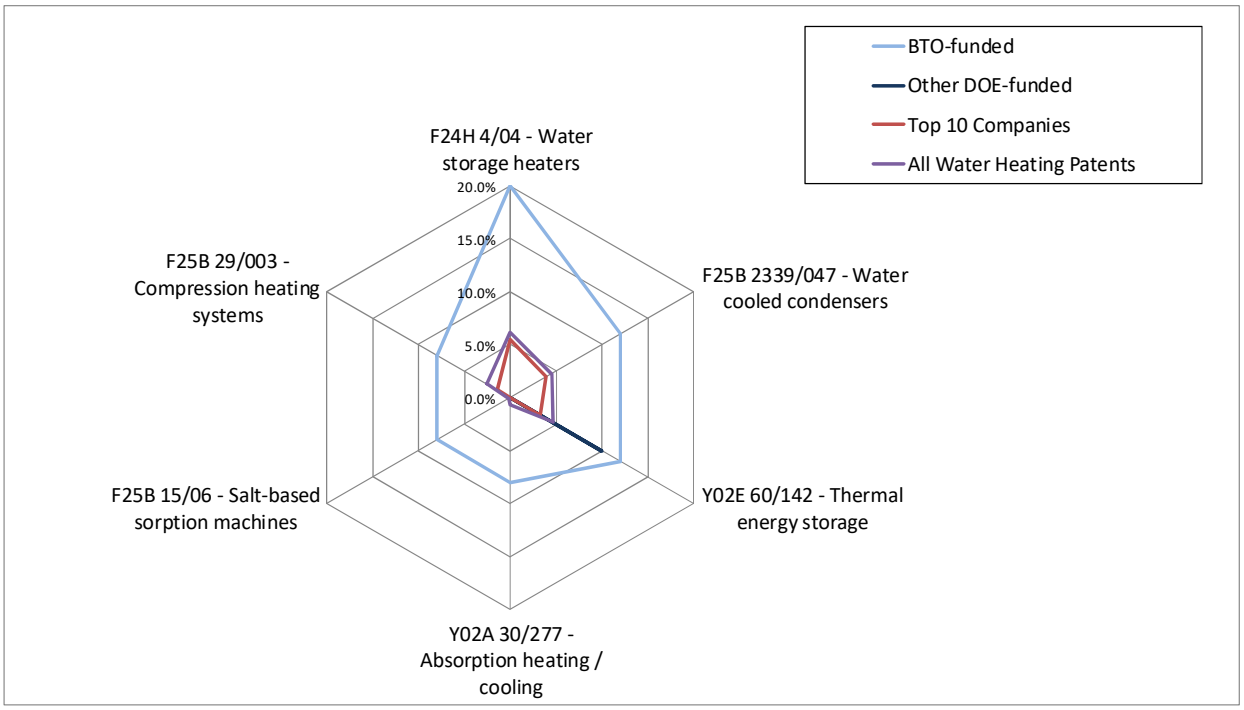
Distribution of Water Heating Patents across Patent Classifications

We analyzed the distribution of BTO-funded water heating U.S. patents across Cooperative Patent Classifications (CPCs).[21] We then compared this distribution to those associated with Other DOE-funded water heating patents; water heating patents assigned to the ten leading companies; and the universe of all water heating patents. This analysis provides insights into the technological focus of BTO funding in water heating, versus the focus of the remainder of DOE, leading water heating companies, and water heating technology in general.

[21] The CPC is a patent classification system. Patent offices attach numerous CPC classifications to a patent, covering the different aspects of the subject matter in the claimed invention. In generating these charts, all CPCs associated with each patent are included.

The results from this CPC analysis are shown in two separate charts, each from a different perspective. The first chart (Figure 6-9) is based on the six CPCs that are most prevalent among BTO-funded water heating patents. The purpose of this figure is thus to show the main focus areas of BTO-funded water heating research, and the extent to which these areas translate to other portfolios (Other DOE-funded; leading water heating companies; all water heating).

Figure 6-9 - Percentage of Water Heating U.S. Patents in Most Common Cooperative Patent Classifications (Among BTO-Funded Patents)



This figure shows that BTO-funded research includes relatively balanced coverage across the six CPCs (which is not particularly surprising, since the BTO-funded patent portfolio forms the basis for the CPCs included in the chart). The most common CPCs among BTO-funded water heating patents is F24H 4/04 (Water storage heaters), with 20% of these patents having this CPC attached. It is followed by F25B 2339/047 (Water cooled condensers), and Y02E 60/142 (Thermal energy storage), with 12% of BTO-funded water heating patents having these CPCs attached. The leading companies also have a notable presence in these CPCs, as do water heating patents overall. Conversely, these portfolios have very little presence in CPCs related absorption-based technologies (F25B 15/06 and Y02A 30/277), CPCs where there are a number of BTO-funded patents. As such, in the period 1976-2018, BTO funding may have helped to fill a research gap not addressed extensively by the leading water heating companies.

Figure 6-10 is similar to Figure 6-9, except that it is from the perspective of the most common CPCs among all water heating patents. Hence, the purpose of this chart is to show the main research areas within water heating as a whole, and how these areas are represented in selected water heating portfolios (BTO-funded; Other DOE-funded; leading water heating companies). None of the six CPCs in Figure 6-9 also appear in Figure 6-10, suggesting that BTO-funded water heating patents have had a somewhat different technological focus to water heating patents in general. The latter are more concentrated in CPCs related to renewable energy building

systems (Y02B 10/70), heaters with fluid combustibles (F24H 9/2035) and water heating furnace tubes (F24H 1/205), the latter being a particular focus of the leading companies.

Figure 6-10 - Percentage of Water Heating U.S. Patents in Most Common Cooperative Patent Classifications (Among All Water Heating Patents)

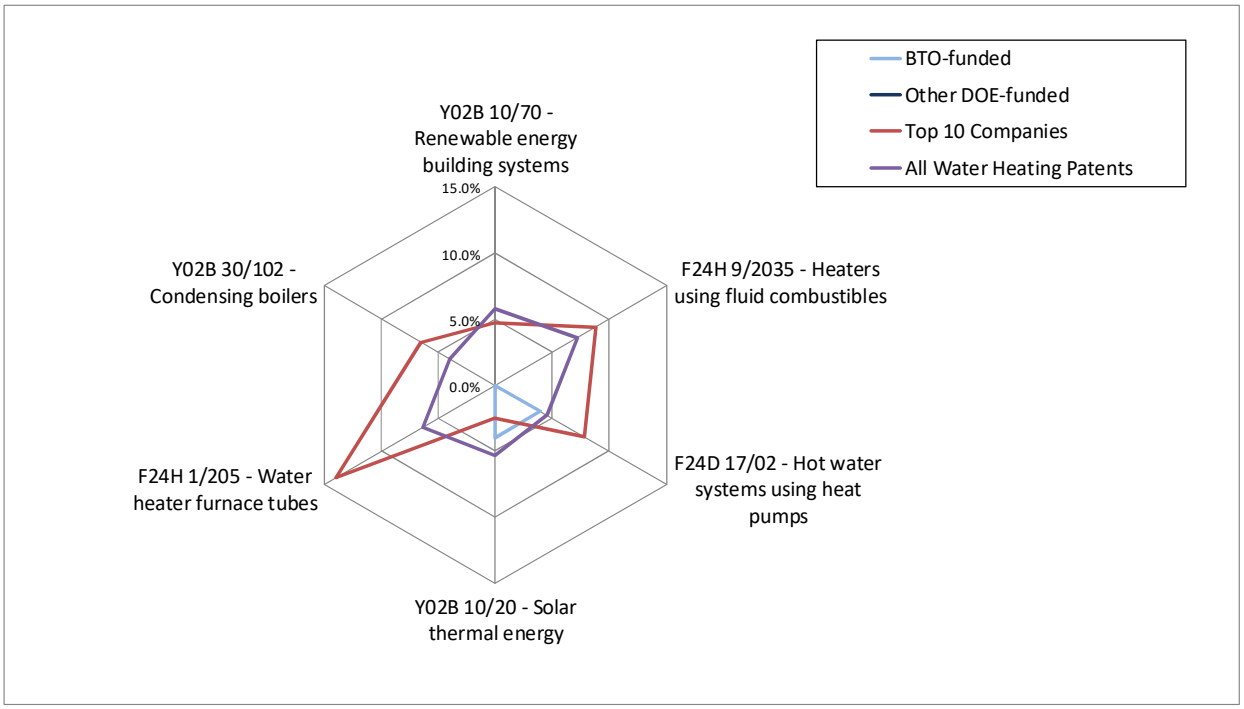


Figure 6-11 - Percentage of BTO-funded Water Heating U.S. Patents in Most Common Cooperative Patent Classifications across Two Time Periods

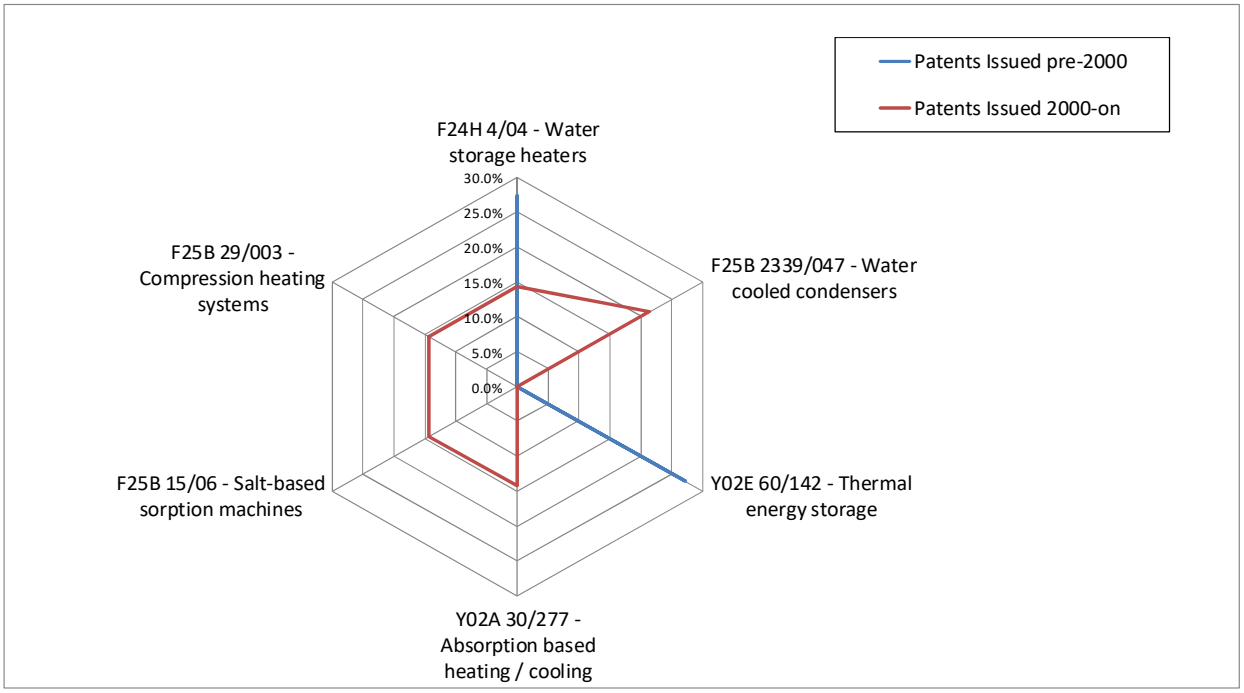


Figure 6-11 compares the CPC distribution of BTO-funded water heating U.S. patents across two time periods – patents issued through 1999, and those issued from 2000 onwards. This figure suggests a change in emphasis in the more recent time period. While BTO-funded patent families filed before 2000 focus on water storage heaters (CPC F24H 4/04) and thermal energy storage (Y02E 60/142), the more recent time period shows a greater concentration on absorption-based technologies (F25B 15/06 and Y02A 30/277). That said, it should be kept in mind that the numbers of patents involved are relatively small.

Tracing Backwards from Water Heating Patents Owned by Leading Companies

This section reports the results of an analysis tracing backwards from water heating patents owned by leading companies in this technology to earlier research, including that funded by BTO (and by DOE in general). The results in this section are examined at two levels. First, we report results at the organizational level. These results reveal the extent to which BTO-funded (and Other DOE-funded) research forms a foundation for subsequent innovations associated with leading water heating companies. Second, we drill down to the level of individual patents, with a particular focus on BTO-funded water heating patents. These patent-level results highlight specific BTO-funded patents that have had a particularly strong influence on subsequent patents owned by leading companies. They also highlight which water heating patents owned by these leading companies are linked particularly extensively to earlier BTO-funded research.

Organizational Level Results

In the organizational level results, we first compare the influence of BTO-funded and Other DOE-funded water heating research against the influence of leading companies in this technology. We then look at which of these leading companies build particularly extensively on DOE-funded water heating research. Figure 6-12 compares the influence of BTO-funded and Other DOE-funded water heating research to the influence of research carried out by the top twelve water heating companies. Specifically, this figure shows the number of water heating patent families owned by the leading companies that are linked via citations to earlier water heating patent families assigned to each of these leading companies (plus patent families funded by DOE). This figure thus shows the companies whose patents have had the strongest influence upon subsequent developments made by leading companies in water heating technology.[22]

A.O. Smith is at the head of Figure 6-12, with 279 water heating patent families owned by the leading companies (i.e. 19% of these 1,471 families) linked via citations to its earlier water heating patents. It is followed by Paloma (157 linked families), United Technologies (110) and Vaillant (90). Thirty leading company patent families are linked via citations to earlier DOE-funded water heating patents, 29 of which are linked BTO-funded water heating patents. This puts DOE-funded patents fourth from last in Figure 6-12.

[22] This figure compares the influence of patents *funded* by BTO/Other DOE against patents *owned* by (i.e. assigned to) organizations. Such a comparison is reasonable, since patents funded by organizations through their R&D budgets will be assigned to those organizations. Also, organizations cannot choose to reference the patents of a non-competitor (such as DOE) rather than the patents of a competitor in order to reduce the "credit" given to that competitor. Such an omission could lead to the invalidation of their patents. Note that in Figure 6-12 and Figures 6-14 – 6-16, leading company patent families linked to both BTO-funded and Other DOE-funded patents are allocated to the BTO-funded segment of the DOE column, in order to avoid double-counting these families.

Figure 6-12 - Number of Leading Company Water Heating Patent Families Linked via Citations to Earlier Water Heating Patents from each Leading Company
e.g. 30 leading company families are linked to earlier BTO/Other DOE-funded families

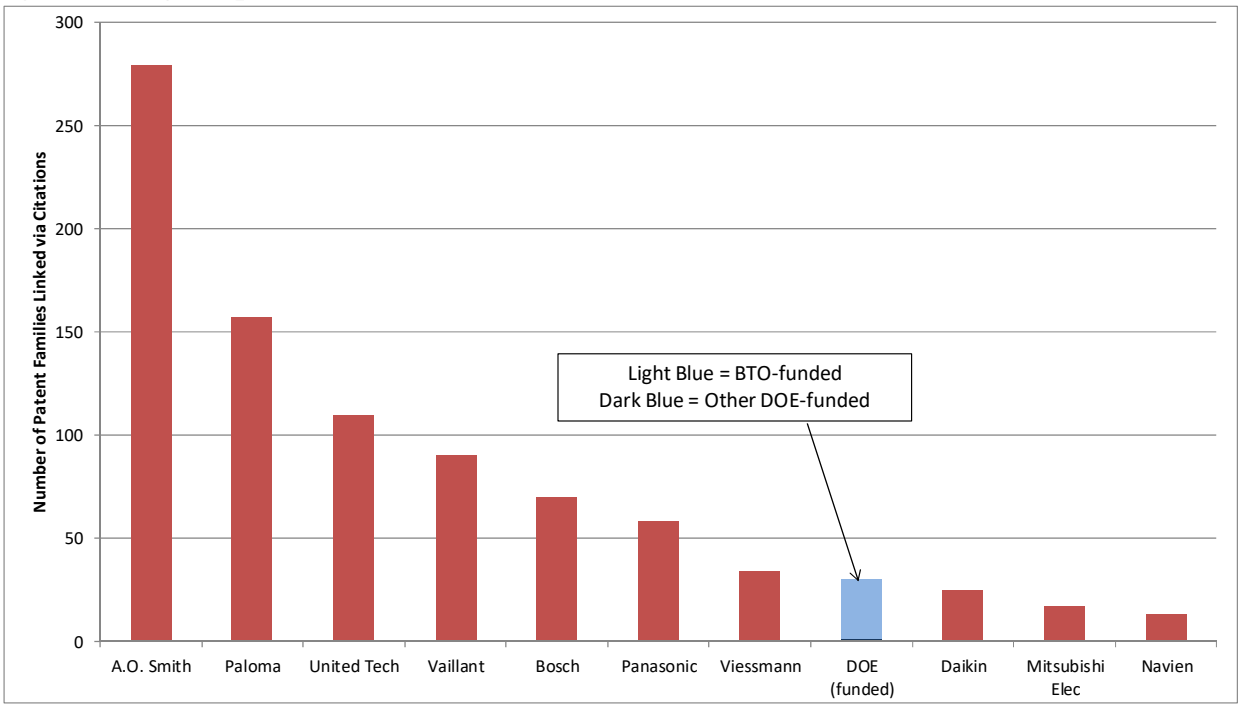
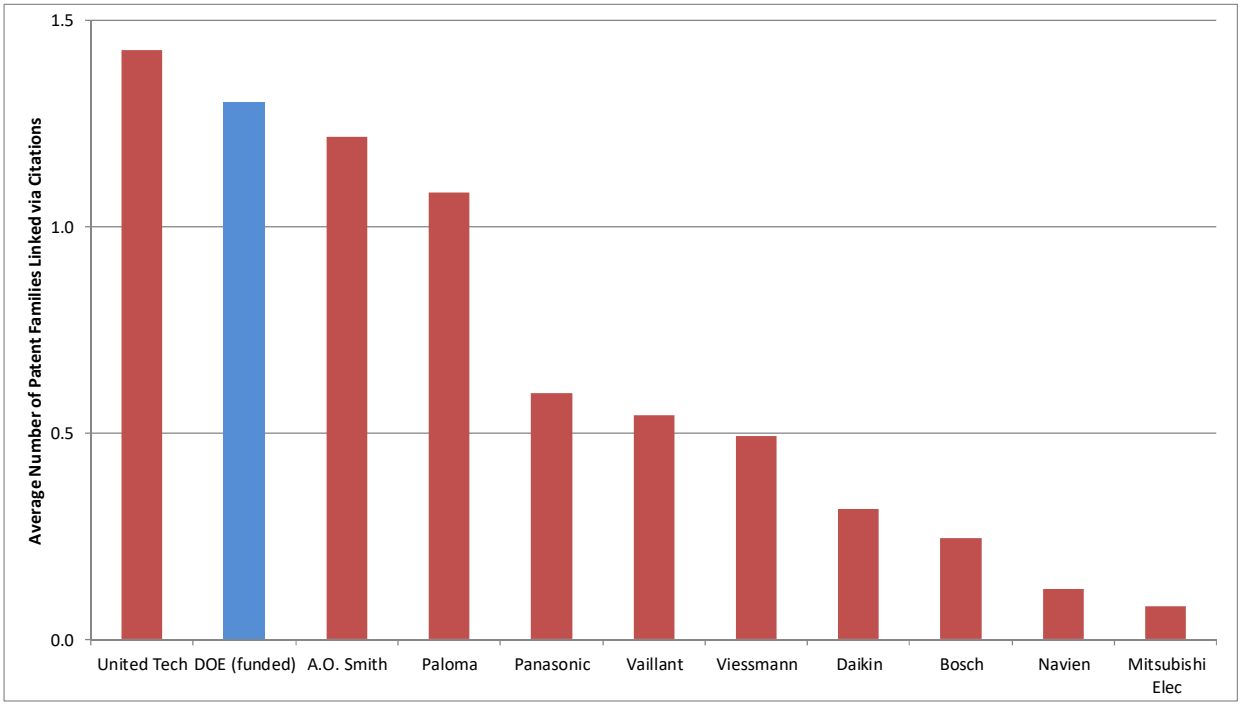


Figure 6-13 – Average Number of Leading Company Water Heating Patent Families Linked via Citations to Water Heating Families from Each Leading Company
e.g. on average, each DOE-funded family is linked to 1.3 subsequent leading company families



At first glance, Figure 6-12 does not appear promising in terms of DOE's influence in water heating technology. However, this figure does not take into account the different sizes of the patent portfolios associated with the various companies. For example, it is not surprising that many more patent families are linked via citations to A.O. Smith than to DOE, since A.O. Smith has almost seven times as many water heating patent families available to be cited as prior art.

Figure 6-13 takes into account the differences in patent portfolio size. It shows the average (mean) number of leading company patent families linked to patent families associated with each of the leading companies, plus DOE. For example, on average, DOE-funded water heating patent families (the majority of which are BTO-funded) are each linked to 1.3 patent families assigned to the leading companies. This puts DOE-funded patents in second place in Figure 6-13, behind only United Technologies (whose patent families are linked to an average of 1.43 leading company families each). It means that, on average, more water heating patent families owned by leading companies are linked via citations to each DOE-funded water heating patent family than are linked to the water heating patent families assigned to any other leading company (except United Technologies). Figure 6-13 thus suggests that, taking into account its relatively small size, the portfolio of DOE-funded water heating patents has had a notable influence on the water heating innovations associated with the leading companies.

Figures 6-14 – 6-16 examine which of the leading companies build particularly extensively on earlier BTO-funded and Other DOE-funded water heating patents. Figure 6-14 shows how many water heating patent families owned by each of the leading companies are linked via citations to earlier DOE-funded water heating patents.

Figure 6-14 - Number of Patent Families Assigned to Leading Water Heating Companies Linked via Citations to Earlier BTO/Other DOE-funded Water Heating Patents

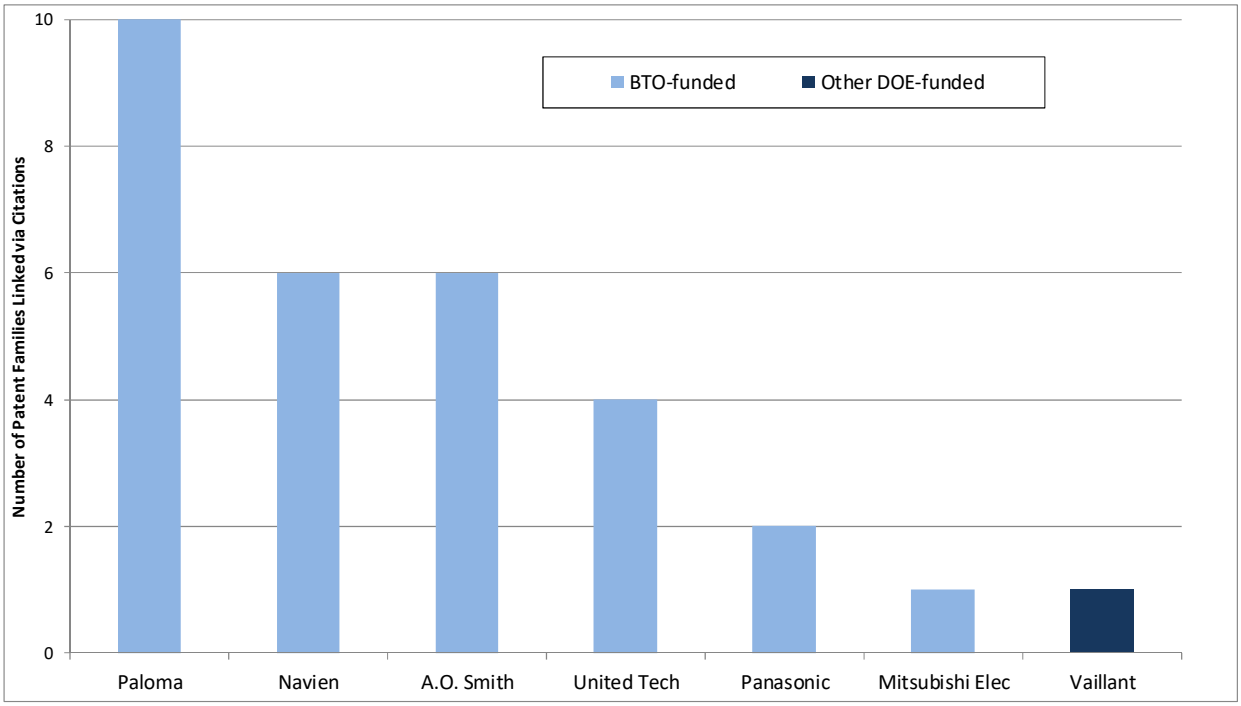
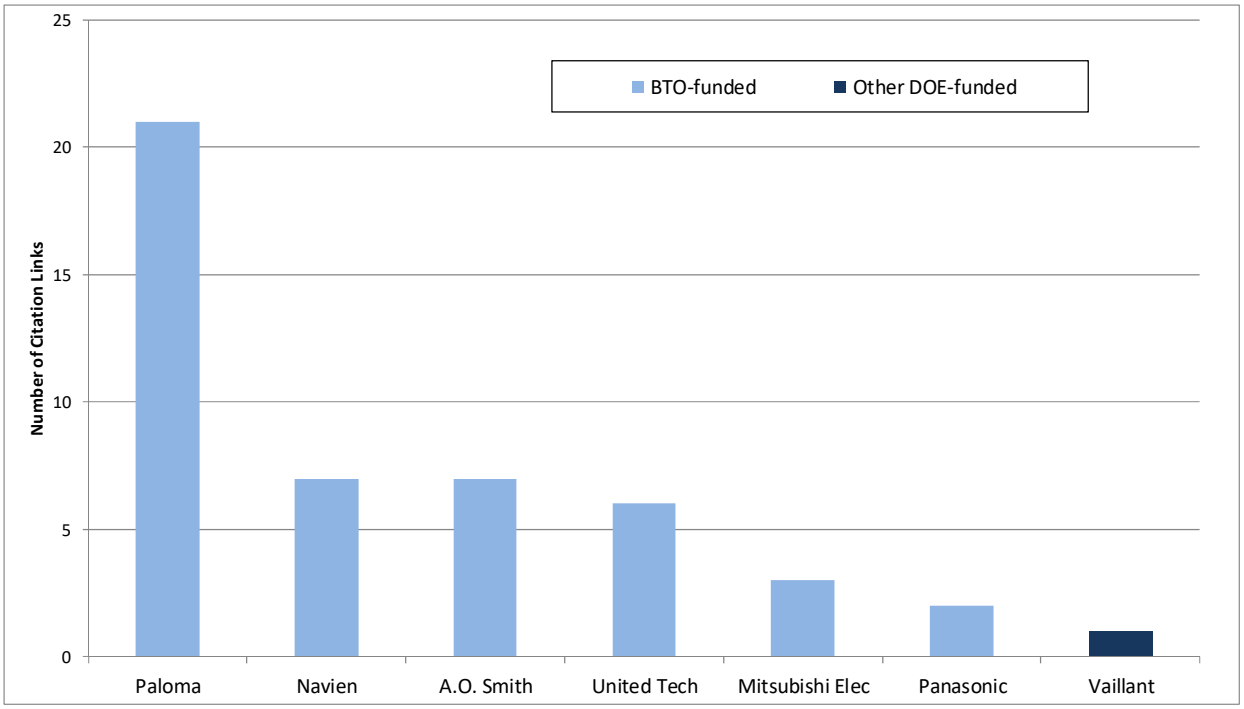


Figure 6-14 reveals that seven out of the ten leading companies have at least one patent family linked via citations to earlier DOE-funded patents. Six of these seven have patent families linked to BTO-funded patents, while the seventh (Vaillant) has one patent family linked to Other DOE-funded patents. Paloma has the largest number of water heating patent families linked to earlier BTO-funded patents (10), followed by Navien (6) and A.O. Smith (6).

Figure 6-15 counts the total number of citation links from leading companies to earlier DOE-funded patents. This differs slightly from the count of linked families in Figure 6-14, since a single patent family may be linked to multiple earlier DOE-funded patents. The same three companies are again at the head of Figure 6-15 – Paloma, Navien and A.O. Smith. The biggest difference between Figures 6-14 and 6-15 is that Paloma leads by a much greater margin in the latter figure, with a total of 21 citation links to earlier BTO-funded patents.

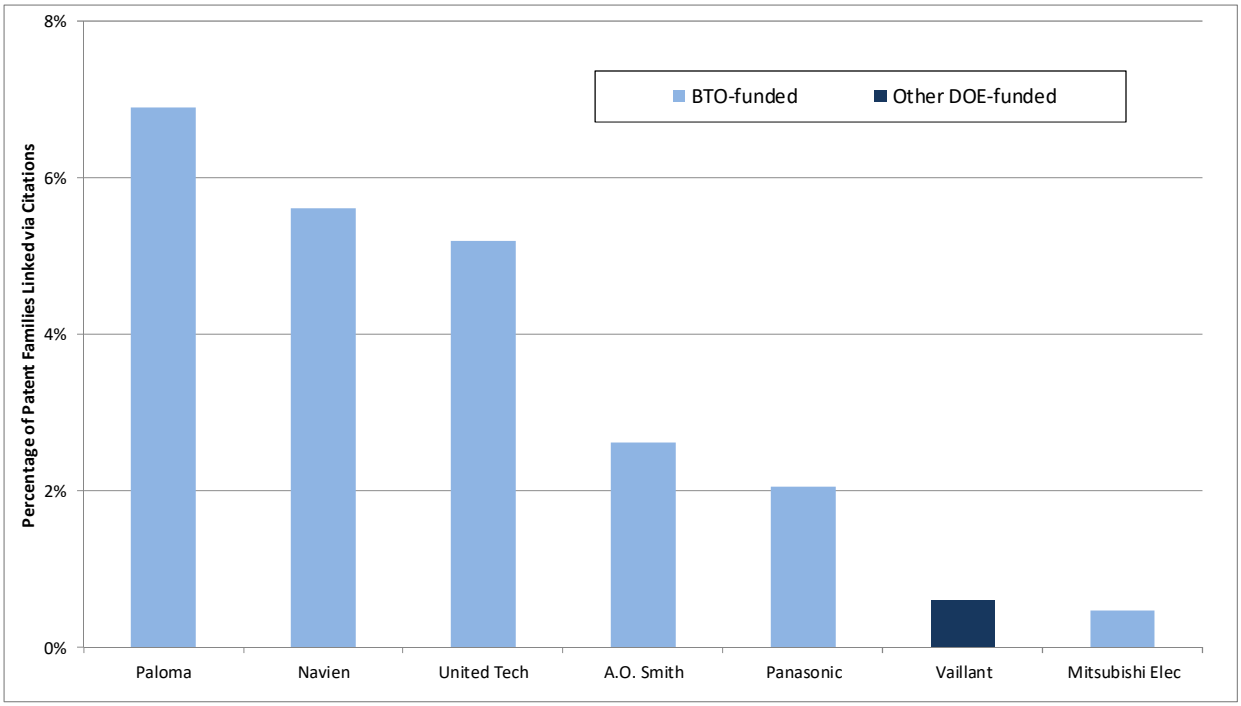
Figure 6-15 - Total Number of Citation Links from Leading Water Heating Company Patent Families to Earlier BTO/Other DOE-funded Water Heating Patents



There is an element of portfolio size bias in the patent family counts in Figures 6-14 and 6-15. Companies with larger water heating patent portfolios are likely to have more patent families linked to DOE, simply because they have more families overall. Figure 6-16 accounts for this portfolio size bias by calculating the percentage of each leading company's water heating patent families that are linked via citations to earlier DOE-funded water heating patents, rather than their absolute number. This is a measure of how extensively each company builds on DOE-funded research, relative to their overall patent output. Figure 6-16 reveals that three of the leading companies have more than 5% of their water heating patent families linked via citations to earlier BTO-funded water heating patents. Paloma heads this list, with 6.9% of its patent families linked via citations to BTO-funded patents, followed by Navien (5.6%) and United Technologies (5.2%). A.O. Smith is slightly less prominent in Figure 6-16, with 2.6% of its

patent families linked via citations to BTO-funded patents. Its higher position in Figures 6-14 and 6-15 was thus due in part to its large number of patent families.

Figure 6-16 - Percentage of Leading Water Heating Company Patent Families Linked via Citations to Earlier BTO/Other DOE-funded Water Heating Patents



Patent Level Results

The previous section of the report examined results at the level of entire patent portfolios. The purpose of this section is to drill down to identify individual DOE-funded water heating patent families (in particular BTO-funded families) that have had a particularly strong influence on subsequent water heating patents owned by leading companies in this technology. Looking in the opposite direction, it also identifies individual water heating patents owned by leading companies that have extensive links to earlier BTO-funded research.

Table 6-1 shows the BTO-funded water heating patent families linked via citations to the largest number of subsequent patent families owned by leading companies in this technology. Three patent families stand out in this table, in terms of the number of leading company patent families linked to them. The patent family at the head of this table (whose representative patent[23] is US #4,390,008) has a priority year of 1980 and is assigned to DOE. It describes a water heating system operated using solar energy. Twelve water heating patent families assigned to the leading companies are linked via citations to this BTO-funded patent family, including patent families assigned to Paloma, A.O. Smith, Panasonic and United Technologies. The BTO-funded patent family in second place in Table 6-1 (representative patent US #5,906,109) is newer, having been filed in 1998. This patent family is assigned to Arthur D. Little, and describes a heat pump hot

[23] The representative patent is a single patent from a family, but it is not necessarily the priority filing.

water tank. It is linked via citations to eleven subsequent water heating patent families assigned to four of the leading companies – Navien, Paloma, A.O. Smith and United Technologies. The third patent family in Table 6-1 is again older, with an initial filing date in 1978. It is assigned to Energy Utilization Systems, and is linked to ten patent families owned by the leading companies, notably families assigned to Navien, Paloma and United Technologies.

Table 6-1 – BTO-Funded Water Heating Patent Families Linked via Citations to Most Subsequent Leading Company Water Heating Patent Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
22590057	4390008	1980	12	US Dept Energy	Hot water tank for use with a combination of solar energy and heat pump desuperheating
22025876	5906109	1998	11	Arthur D Little Inc	Heat pump water heater and storage tank assembly
25363516	4173872	1978	10	Energy Utilization Systems	Water heater apparatus
23565684	6233958	1999	4	Lockheed Martin (ORNL)	Heat pump water heater and method of making the same
23704539	4523629	1982	2	US Dept Energy	Method and apparatus for operating an improved thermocline storage unit
26863957	6675746	1999	2	Advanced Mechanical Tech	Heat exchanger with internal pin elements
48653410	8756943	2011	2	Nordyne LLC	Refrigerant charge management in a heat pump water heater

Table 6-1 lists BTO-funded patents linked to the largest number of subsequent water heating patent families owned by leading companies. Table 6-2 looks in the opposite direction, and lists water heating patent families owned by leading companies that are linked via citations to multiple BTO families.

Table 6-2 - Leading Company Water Heating Patent Families Linked via Citations to Largest Number of BTO-Funded Water Heating Patent Families

Patent Family #	Representative Patent #	Priority Year	# BTO Fams	Assignee	Title
43647836	8385729	2009	5	Paloma Industries	Heat pump water heater and associated control system
49477366	9157655	2013	3	Paloma Industries	Endothermic base-mounted heat pump water heater
49160344	9644876	2012	3	Mitsubishi Electric	Refrigeration cycle apparatus
51568125	9488384	2014	2	United Technologies	Heat pump water module with condensing coil in water storage tank
56367299	10036570	2015	2	Paloma Industries	Heat transfer baffle arrangement for fuel-burning water heater
32711426	7458418	2005	2	United Technologies	Storage tank for hot water systems
52483810	9939173	2013	2	Navien Co Ltd	System for controlling exhaust heat recovery temperature using mixing valve and method therefor
51531497	9405304	2013	2	A.O. Smith Corp	Water heater and method of operating a water heater

Paloma has the two patent families at the head of Table 6-2. The first of these patent families (representative patent US #8,385,729) describes a heat pump water heater. It is linked via citations to five earlier BTO-funded patent families, including the three families highlighted above at the head of Table 6-1. The second Paloma patent family in Table 6-2 (representative patent US #9,157,655) also describes a heat pump water heater. It is linked to three earlier BTO-funded patents families, including the Arthur D. Little and Energy Utilization Systems families highlighted in Table 6-1, plus a Lockheed Martin (Oak Ridge National Laboratory) family describing a heat pump water heater (listed in fourth in Table 6-1). Mitsubishi Electric has the patent family in third place in Table 6-2 (representative patent US #9,644,876). This family describes a vapor-compression refrigeration cycle apparatus, and is linked to three earlier BTO-funded patents outlining refrigerant charge management in heat pump water heaters.

We also identified high-impact water heating patents owned by the leading companies that have citation links back to BTO-funded patents.[24] The idea is to highlight important technologies owned by leading companies that are linked to earlier BTO-funded water heating research. Table 6-3 lists leading company patents that are linked via citations to BTO-funded patents, and in turn have been cited more frequently than expected given their age and technology (i.e. they have Citation Index values above one).

Table 6-3 - Highly Cited Leading Company Water Heating Patents Linked via Citations to Earlier BTO-funded Water Heating Patents

Patent	Issue Year	# Cites Received	Citation Index	Assignee	Title
7458418	2008	24	3.19	United Technologies	Storage tank for hot water systems
8385729	2013	6	1.65	Paloma Industries	Heat pump water heater and associated control system
7258080	2007	18	1.33	Paloma Industries	Fuel-fired dual tank water heater having dual pass condensing type heat exchanger

The patent at the head of Table 6-3 (US #7,458,418) is assigned to United Technologies and describes a hot water tank with a mechanical insulator to separate the hot layer and cold layer. Since being issued in 2008, this patent has been cited as prior art by 24 subsequent patents, more than three times as many citations as expected given its age and technology. In turn, this United

[24] High-impact patents are identified using 1790's Citation Index metric. This metric is derived by first counting the number of times a patent is cited as prior art by subsequent patents. This number is then divided by the mean number of citations received by peer patents from the same issue year and technology (as defined by their first listed Cooperative Patent Classification). For example, the number of citations received by a 2010 patent in CPC F24H 4/04 (Water storage heaters) is divided by the mean number of citations received by all patents in that CPC issued in 2010. The expected Citation Index for an individual patent is one. The extent to which a patent's Citation Index is greater or less than one reveals whether it has been cited more or less frequently than expected, and by how much. For example, a Citation Index of 1.5 shows that a patent has been cited 50% more frequently than expected. Meanwhile a Citation Index of 0.7 reveals that a patent has been cited 30% less frequently than expected. By extension, the expected Citation Index for a portfolio of patents is also one, with values above one showing that a portfolio has been cited more than expected, and values below one showing that a portfolio has not been cited as frequently as expected. Note that the Citation Index is calculated for U.S. patents only, due to the differences in citation practices across different countries' patent systems.

Technologies patent is linked via citations to two earlier BTO-funded water heating patents assigned to DOE, including the solar energy water heating patent at the head of Table 6-1. The second patent in Table 6-3 (US #8,385,729) is assigned to Paloma, and is part of the patent family at the head of Table 6-2. This patent, which is linked via citations to five different BTO-funded water heating patent families, has in turn been cited as prior art by six subsequent patents, 65% more citations than expected. Paloma is also the assignee on the third patent in Table 6-3 (US #7,258,080), which has been cited by 18 subsequent patents (33% more than expected). This Paloma patent describes a dual-tank water heating system, and is again linked via citations to the solar energy water heating patent assigned to DOE at the head of Table 6-1.

While the patent-level results focus on BTO-funded water heating patent families, we also identified Other DOE-funded water heating families linked to subsequent patent families owned by leading companies in this technology. As shown above in Figure 6-15, there is only one citation link between Other DOE-funded water heating patents and subsequent leading company patents. The cited Other DOE-funded patent family (representative patent US #4,411,307) is shown in Table 6-4. It is assigned to Atlantic Richfield, and describes a double-walled heat exchanger. This patent family is linked via citations to a subsequent Vaillant family outlining a heat pipe for a water heating system.

Table 6-4 - Other DOE-Funded Water Heating Patent Families Linked via Citations to Most Subsequent Leading Company Water Heating Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
22860749	4411307	1981	1	Atlantic Richfield	Wound tube heat exchanger

Overall, the backward tracing element of the analysis suggests that, given their relatively small size, the portfolios of DOE-funded (and especially BTO-funded) water heating patents have had a notable influence on subsequent innovations associated with leading companies in this technology. This influence can be seen both over time and across these leading companies, with their innovations related to heat pump water heaters and refrigeration cycles linked via citations to earlier BTO-funded water heating patents.

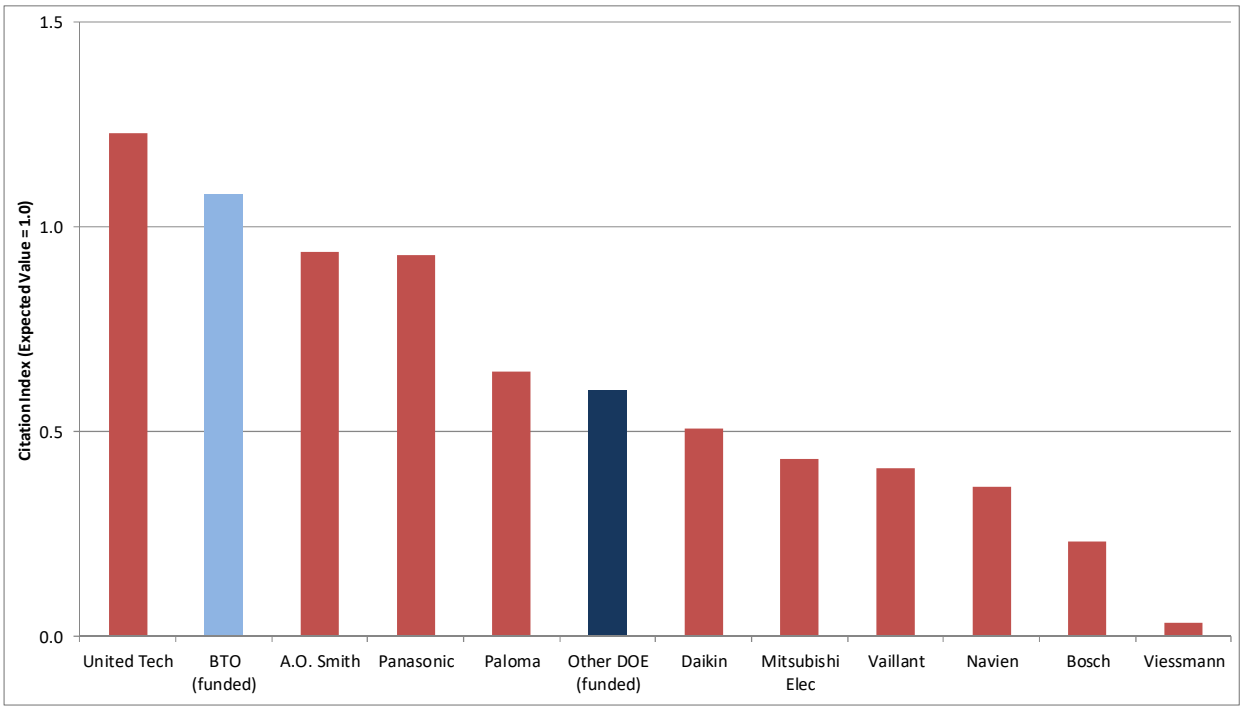
Tracing Forwards from DOE-funded Water Heating Patents

The previous section of the report examines the influence of DOE-funded water heating research upon technological developments associated with leading water heating companies. That analysis was based on tracing backwards from the patents of leading companies to previous generations of research. This section reports the results of an analysis tracing in the opposite direction – starting with BTO-funded (and Other DOE-funded) water heating patents, and tracing forwards in time through two generations of citations. Hence, while the previous section of the report focuses on DOE's influence upon a specific patent set (i.e. patents owned by leading water heating companies), this section of the report focuses on the broader influence of BTO-funded (and Other DOE-funded) water heating research, both within and beyond water heating technology. Also, in order to avoid repeating earlier results, the forward tracing concentrates primarily on patents that are linked to DOE-funded water heating research, but are not owned by leading water heating companies.

Organizational Level Results

We first generated Citation Index values for the portfolios of BTO-funded and Other DOE-funded water heating patents. We then compared these Citation Indexes against those of the ten leading water heating companies. The results are shown in Figure 6-17. This figure reveals that BTO-funded water heating patents have a Citation Index of 1.08, showing they have on average been cited 8% more frequently than expected given their age and technology. This puts BTO-funded patents in second place in Figure 6-17, behind only United Technologies (which has a Citation Index of 1.23). These are the only two patent portfolios with a Citation Index above one. This suggests that BTO-funded water heating patents have had a moderately strong overall influence on subsequent innovations. Other DOE-funded patents have a lower Citation Index of 0.60 (i.e. 40% fewer citations than expected), putting them in sixth place in Figure 6-17.

Figure 6-17 - Citation Index for Leading Companies' Water Heating Patents, plus BTO-funded and Other DOE-funded Water Heating Patents



The Citation Index metric measures the overall influence of the DOE-funded water heating patent portfolios, but does not necessarily address the breadth of this influence across technologies. We therefore identified the Cooperative Patent Classifications (CPCs) of the patent families linked via citations to earlier BTO-funded (and Other DOE-funded) water heating patent families.[25] These CPCs reflect the influence of DOE-funded research across technologies.

Figure 6-18 shows the CPCs with the largest number of patent families linked via citations to BTO-funded water heating patents. The CPCs in this figure are shown in two different colors –

[25] Patents typically have numerous CPCs attached to them, reflecting different aspects of the invention they describe. In this analysis, we include all CPCs attached to the patents linked to earlier DOE-funded water heating patent families.

i.e. dark green for CPCs related to water heating technology and light green for CPCs beyond water heating. Nine of the fourteen CPCs in this figure are related to technologies beyond water heating. The two CPCs at the head of the figure are concerned with semiconductor manufacturing, with technologies related to heating and cooling semiconductor devices (CPC H01L 23/473) leading to further links to connecting semiconductor devices (CPC H01L 2924/00). Also prominent in Figure 6-18 are CPCs related to solar thermal energy (Y02B 10/20 and Y02E 10/47) and power plants (Y02E 20/16 and F02C 3/34). These are examples of the influence of BTO-funded water heating patents extending into other technologies.

Figure 6-18 - Number of Patent Families Linked via Citations to Earlier BTO-Funded Water Heating Patents by CPC (Dark Green = Water Heating; Light Green = Other)

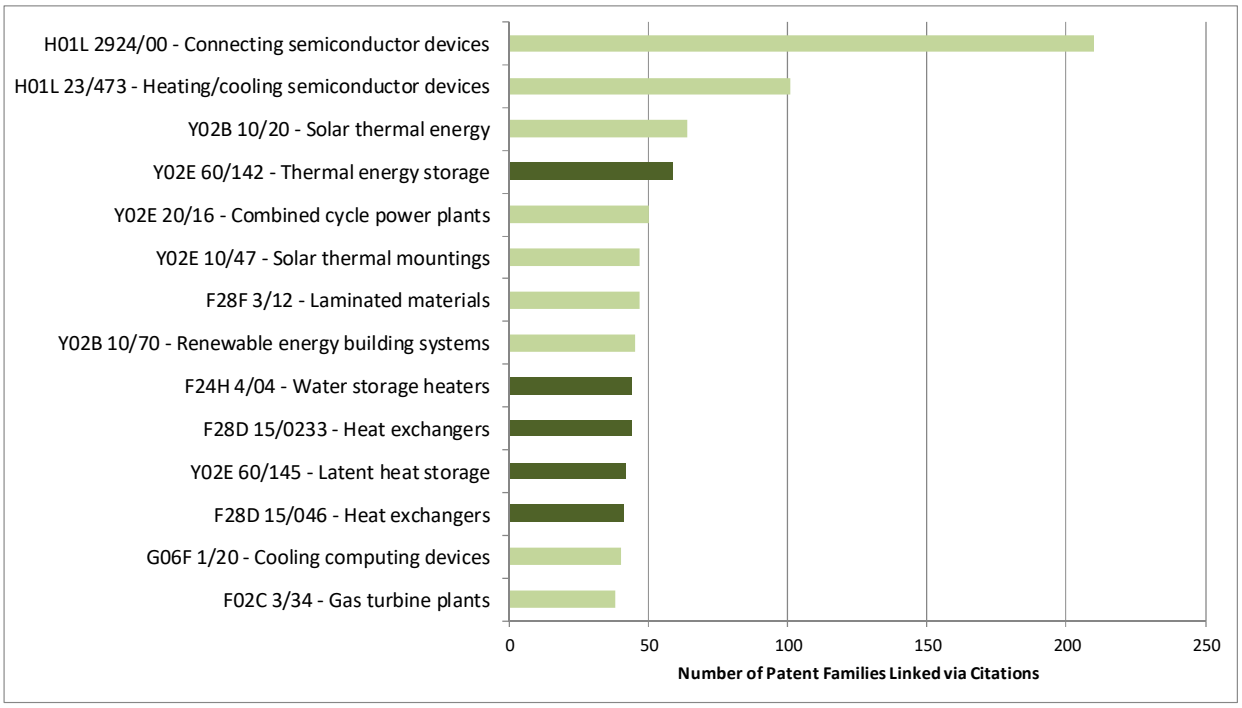


Figure 6-19 is similar to Figure 6-18, but is based on patent families linked to Other DOE-funded water heating patents, rather than BTO-funded water heating patents. Seven of the thirteen CPCs in Figure 6-19 are concerned with technologies beyond water heating. CPCs related to semiconductor manufacturing (H01L 2924/00 and H01L 23/427) are again prominent, as are CPCs concerned with power plants (Y02E 20/16 and F02C 3/34). Figure 6-19 also includes CPCs for cooling aircraft blades (Y02T 50/677) and computer devices (G06F 1/20). Again, these are examples of the influence of BTO-funded water heating patents extending into other technologies.

The organizations with the largest number of patent families linked via citations to earlier BTO-funded water heating patents are shown in Figure 6-20. To avoid repeating the results from earlier, this figure excludes the twelve leading water heating companies used in the backward tracing element of the analysis. Also, note that Figure 6-20 includes all patent families assigned to these organizations, not just their families describing water heating technology.

Figure 6-19 – No. of Patent Families Linked via Citations to Earlier Other DOE-Funded Water Heating Patents by CPC (Dark Green = Water Heating; Light Green = Other)

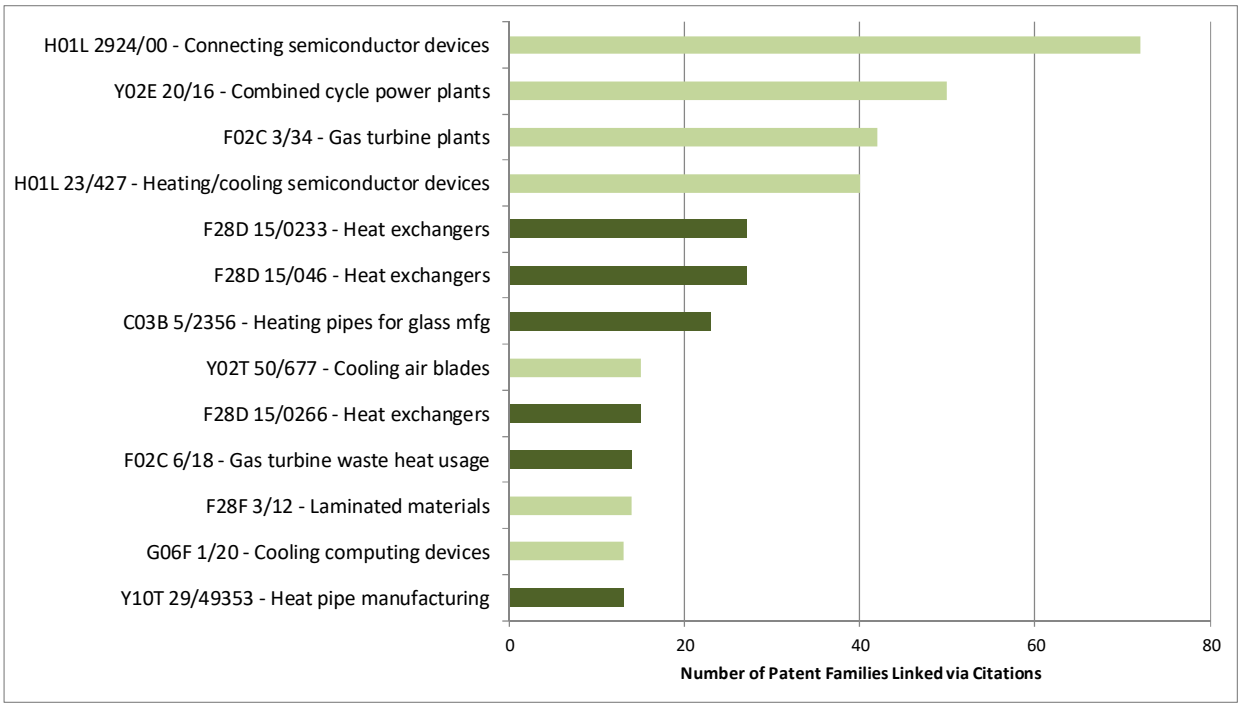


Figure 6-20 - Organizations with Largest No. of Patent Families Linked via Citations to BTO-funded Water Heating Patents (excluding leading water heating companies)

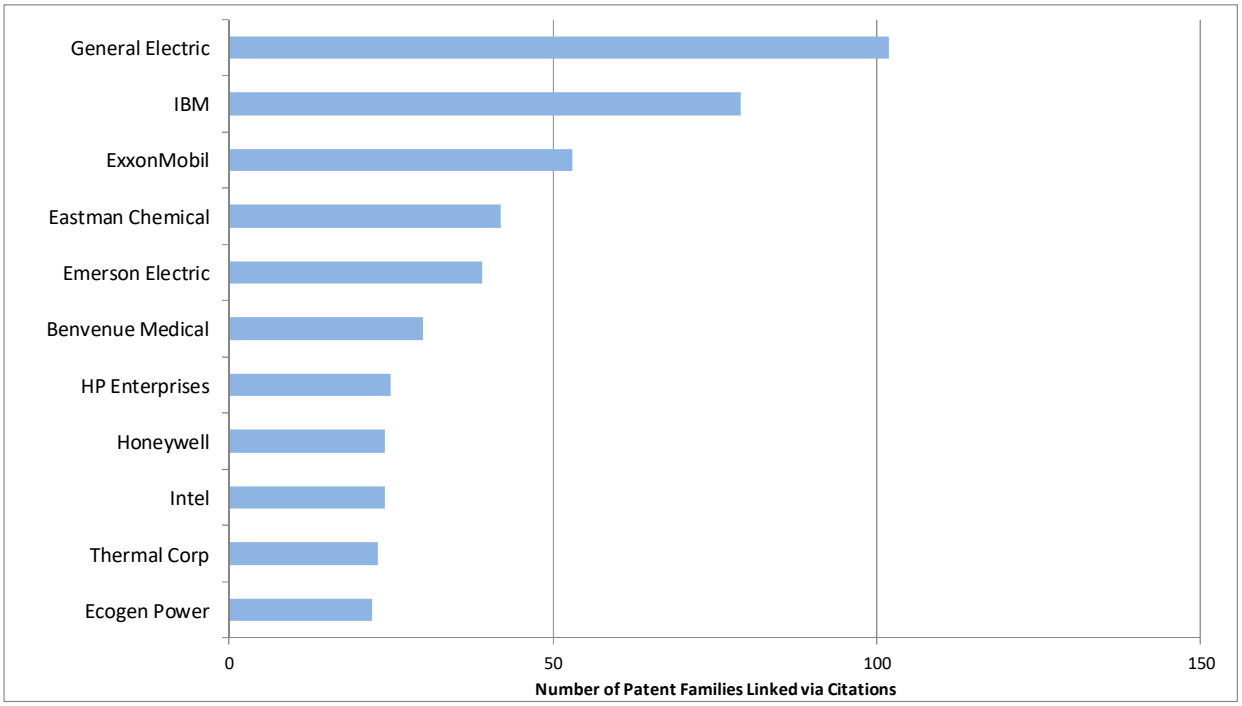
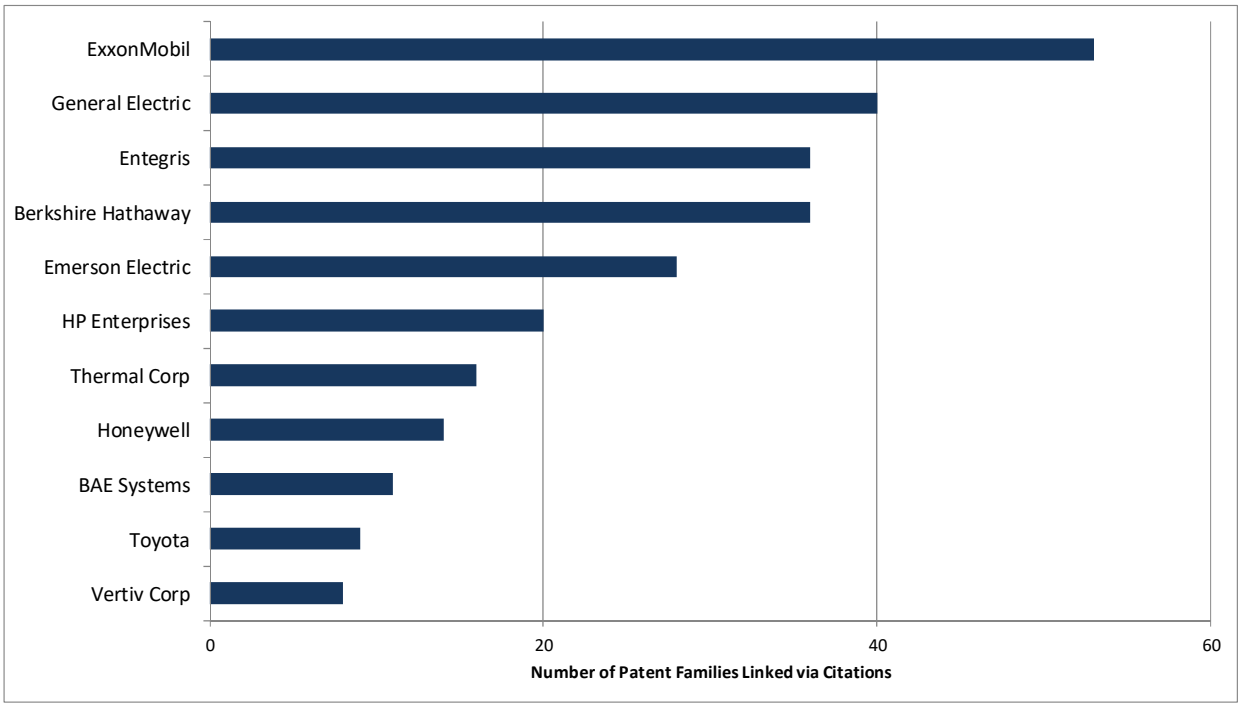


Figure 6-20 contains various very large companies with interests in many technologies. This figure is headed by General Electric, with 102 patent families linked via citations to earlier BTO-

funded water heating patents, many of them related to energy management for domestic appliances and power plants. IBM is in second place in Figure 6-20, with 79 patent families linked to BTO-funded patents. These IBM patent families describe heating and cooling for various applications, including electronics, computing and semiconductors. ExxonMobil has 53 patent families linked to earlier BTO-funded water heating patents, with a primary focus on gas turbines and power generation.

Figure 6-21 shows the organizations with the largest number of patent families linked via citations to earlier Other DOE-funded water heating patents. This figure contains a number of the companies featured in Figure 6-20, which focused on patent families linked to earlier BTO-funded water heating patents. These include ExxonMobil and General Electric, the two companies at the head of Figure 6-21. ExxonMobil has 53 patent families linked via citations to earlier Other DOE-funded patents, many of them concerned with gas turbines. Meanwhile, General Electric has 40 patent families in Figure 6-21, with a primary focus on power generation and gas turbine technology.

Figure 6-21 - Organizations with Largest No. of Patent Families Linked via Citations to Other DOE-funded Water Heating Patents (excluding leading water heating companies)



Patent Level Results

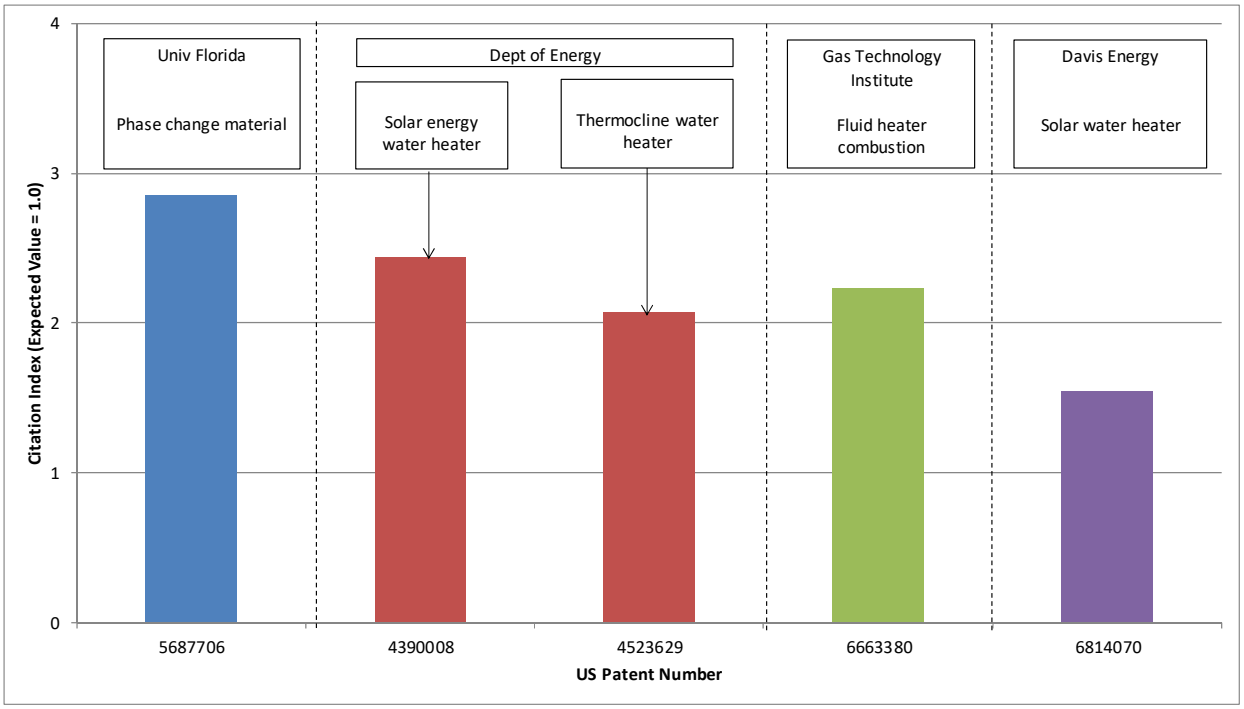
This section of the report drills down to identify individual DOE-funded (and particularly BTO-funded) water heating patents whose influence on subsequent technological developments has been particularly strong. It also highlights patents that have extensive citation links to earlier BTO-funded water heating research. The simplest way of identifying high-impact BTO-funded water heating patents is via overall Citation Indexes. The BTO-funded patents with the highest Citation Indexes are shown in Table 6-5, with selected patents also presented in Figure 6-22.

Table 6-5 – List of Highly Cited BTO-Funded Water Heating Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
5687706	1997	47	2.85	Univ Florida	Phase change material storage heater
4390008	1983	25	2.44	US Dept Energy	Hot water tank for use with a combination of solar energy and heat pump desuperheating
6663380	2003	21	2.23	Gas Technology Institute	Method and apparatus for advanced staged combustion utilizing forced internal recirculation
4523629	1985	29	2.07	US Dept Energy	Method and apparatus for operating an improved thermocline storage unit
6814070	2004	15	1.54	Davis Energy Group	Molded polymer solar water heater

The patent at the head of Table 6-5 (US #5,687,706) was issued in 1997, and assigned to the University of Florida. This patent describes water heaters employing phase change materials to store heat. It has been cited as prior art by 47 subsequent patents, almost three times as many citations as expected given its age and technology. The second patent in Table 6-5 (US #4,390,008) was issued in 1983 and assigned to DOE. This patent, which describes solar energy water heaters, has been cited as prior art by 25 subsequent patents, more than twice as many as expected. It was also highlighted in the backward tracing element of the analysis due to its extensive citation links to water heating patents assigned to the leading companies. The third patent in Table 6-5 (US #6,663,380) is somewhat newer, having been issued in 2003, since when it has been cited by 21 subsequent patents (more than twice as many as expected). It is assigned to Gas Technology Institute, and describes improved combustion for fluid heaters.

Figure 6-22 – Examples of Highly-Cited BTO-funded Water Heating Patents



The Citation Indexes in Table 6-5 are based on a single generation of citations to BTO-funded water heating patents. Tables 6-6 and 6-7 extend this by examining a second generation of

citations – i.e. they show the BTO-funded water heating patents linked directly or indirectly to the largest number of subsequent patent families.[26] These subsequent families are divided into two groups, according to whether they are within or beyond water heating technology (i.e. whether they are in the water heating patent universe constructed in the initial step of this project). This provides insights into which BTO-funded patent families have been particularly influential within water heating, and which have had a broader impact beyond this technology.

Table 6-6 contains older BTO-funded patent families, with priority dates prior to 1999. Two patent families stand out in this table, in terms of the number of subsequent patent families linked to them via citations.

Table 6-6 – Pre-1999 BTO-funded Water Heating Patent Families Linked via Citations to Largest Number of Subsequent Water Heating/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Water Heating Fams	Assignee	Title
22346450	1980	4248295	385	1	Thermacore Inc	Freezable heat pipe
23700908	1995	5687706	374	21	Univ Florida	Phase change material storage heater
22590057	1980	4390008	167	62	US Dept Energy	Hot water tank for use with a combination of solar energy and heat pump desuperheating
22876939	1981	4336837	143	2	US Dept Energy	Entirely passive heat pipe apparatus capable of operating against gravity
22025876	1998	5906109	132	51	Arthur D Little Inc	Heat pump water heater and storage tank assembly
26713783	1979	4361135	126	2	US Dept Energy	Cooperative heat transfer and ground coupled storage system
25363516	1978	4173872	113	54	Energy Utilization Systems	Water heater apparatus
24886368	1991	5143149	91	16	Westinghouse Savannah River (SRS)	Wastewater heat recovery apparatus
23704539	1982	4523629	31	4	US Dept Energy	Method and apparatus for operating an improved thermocline storage unit

The patent family at the head of Table 6-6 (representative patent US #4,248,295) was filed in 1980 and assigned to Thermacore. It outlines a heat pipe that can be frozen and thawed repeatedly without damage. This patent family is linked to 385 subsequent patent families, only one of which is related to water heating, with many of the other linked families describing heating and cooling applications, notably for computing and electronic devices. The second patent family in Table 6-6 (representative patent US #5,687,706) is assigned to the University of

[26] The BTO-funded patent families are divided into two tables based on their age, since older patents tend to be connected to larger numbers of subsequent patents, simply because there has been more time for them to become linked to future generations of technology.

Florida, and describes a storage heater incorporating a phase change material. This patent family (which contains the patent at the head of Table 6-5) is linked via citations to 374 subsequent families, 21 of which are related to water heating, with many of the other linked families describing advanced materials. There are patent families in Table 6-6 that have more extensive citation links within water heating, including the families assigned to DOE, Arthur D. Little and Energy Utilization Systems highlighted earlier in the backward tracing element of the analysis (see Table 6-1).

Table 6-7 contains more recent BTO-funded patent families, with priority dates from 1999 onwards. The patent family at the head of this table is assigned to Gas Technology Institute, and describes improved combustion for fluid heaters. This family (which contains the highly-cited patent US #6,663,380 highlighted in Table 6-5), is linked via citations to 94 subsequent patent families. Only two of these linked families are related to water heating, with many others describing combustion systems, especially for gas turbines. The patent family in second place in Table 6-7 (representative patent US #6,814,070) is assigned to Davis Energy, and describes a solar water heater. This family is linked via citations to 63 subsequent patent families, all from beyond water heating technology, with a particular focus on solar energy applications. The patent family in third place in Table 6-7 (representative patent US #6,233,958) has stronger citation links within water heating technology, with 23 of the 61 subsequent patent families linked to it being related to water heating. This patent family is assigned to Lockheed Martin, through its management of Oak Ridge National Laboratory, and describes a heat pump water heater.

Table 6-7 – Post-1998 BTO-funded Water Heating Patent Families Linked via Citations to Largest Number of Subsequent Water Heating/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Water Heating Fams	Assignee	Title
25484483	2001	6663380	94	2	Gas Technology Institute	Method and apparatus for advanced staged combustion utilizing forced internal recirculation
32681039	2003	6814070	63	0	Davis Energy Group	Molded polymer solar water heater
23565684	1999	6233958	61	23	Lockheed Martin (ORNL)	Heat pump water heater and method of making the same
26863957	1999	6675746	32	7	Advanced Mechanical Tech	Heat exchanger with internal pin elements
35798687	2004	7028490	13	2	UT-Battelle (ORNL)	Water-heating dehumidifier

The tables above identify BTO-funded water heating patent families linked particularly strongly to subsequent technological developments. Table 6-8 looks in the opposite direction, and identifies highly-cited patents linked to earlier BTO-funded water heating patents. As such, these are examples where BTO-funded water heating research has formed part of the foundation for subsequent high-impact technologies. This table focuses on patent families not owned by the leading water heating companies, since those families were examined in the backward tracing element of the analysis.

The patent at the head of Table 6-8 (US #8,367,984) is assigned to General Electric, and describes a method for managing energy consumption by domestic appliances, especially water heaters. Since it was issued in 2013, this patent has been cited as prior art by 68 subsequent patents, almost twenty times as many citations as expected given its age and technology. In turn, this General Electric is linked via citations to the Arthur D. Little heat pump patent family (representative patent US #5,906,109) highlighted earlier in this analysis. The second patent in Table 6-8 (US #8,938,932) is assigned to Quick Mount PV, and describes a roof mounting system for photovoltaic arrays. This patent has been cited by 44 subsequent patents since it was issued in 2015, more than fourteen times as many citations as expected. In turn, this Quick Mount patent is linked to the earlier BTO-funded solar water heating patent assigned to Davis Energy (see Table 6-7). The third patent in Table 6-8 (US #9,035,222) describes a heated travel mug or bottle, and is assigned to Ember Technologies. It has been cited by 33 subsequent patents (thirteen times as many as expected), and is in turn linked to the BTO-funded University of Florida patent family for phase change materials highlighted above (see Table 6-5). The remaining patents in Table 6-8 describe a variety of technologies, including heat exchangers, electronic device cooling and smart ranges. These are examples of BTO-funded water heating patents influencing developments across various technologies.

Table 6-8 - Highly Cited Patents (not from Leading Water Heating Companies) Linked via Citations to Earlier BTO-funded Water Heating Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
8367984	2013	68	19.31	General Electric	Energy management of household appliances
8938932	2015	44	14.24	Quick Mount PV	Rail-less roof mounting system
9035222	2015	33	13.21	Ember Technologies	Heated or cooled dishware and drinkware
7836597	2010	40	11.96	Emerson Electric	Method of fabricating high surface to volume ratio structures and their integration in microheat exchangers
8336319	2012	41	8.58	Tesla Motors	Thermal management system with dual mode coolant loops
6953919	2005	87	8.27	HR Technology Inc	RFID-controlled smart range and method of cooking and heating
7156159	2007	63	7.91	Emerson Electric	Multi-level microchannel heat exchangers
8223495	2012	39	7.20	Exaflop LLC	Electronic device cooling system
6167948	2001	136	6.72	Novel Concepts Inc	Thin, planar heat spreader

As with the backward tracing element of the analysis, the patent-level results from the forward tracing focus on BTO-funded water heating patents. That said, within the forward tracing, we did also identify Other DOE-funded water heating patent families linked to the largest number of subsequent patent families within and beyond water heating technology. These Other DOE-funded water heating families are shown in Table 6-9.

The patent family at the head of Table 6-9 (representative patent US #4,478,275) was filed in 1983 and assigned to Thermacore. It describes a heat pipe for use in corrosive or abrasive environments, and is linked to 180 subsequent patent families, all from outside water heating. These linked families cover a variety of technologies, from hydrogen storage to cooling semiconductor devices. The second patent family in Table 6-9 is newer, having been filed in 2005. This family (representative patent US #6,971,336) is assigned to Gas Technology Institute, and describes a firetube boiler with reduced NOx emissions. It is linked via citations to 113

subsequent patent families (only one within water heating), many of which are concerned with NOx abatement technologies. The third patent family (representative patent US #4,411,307) is assigned to Atlantic Richfield and outlines a double-walled heat exchanger. This is the only Other DOE-funded patent family with a citation link to a leading water heating company (see Table 6-4). All of its other citation links are outside water heating, notably to patents describing fluid pumps with applications in the semiconductor industry.

Table 6-9 - Other DOE-funded Water Heating Patent Families Linked via Citations to Largest Number of Subsequent Water Heating/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Water Heating Fams	Assignee	Title
24056441	1983	4478275	180	0	Thermacore Inc	Abrasion resistant heat pipe
35430271	2005	6971336	113	1	Gas Technology Institute	Super low NOx, high efficiency, compact firetube boiler
22860749	1981	4411307	63	1	Atlantic Richfield	Wound tube heat exchanger
21694983	2001	6722358	22	2	Fafco Inc	Integral collector storage system with heat exchange apparatus
36144293	2004	7066396	22	0	Gas Technology Institute	Method and apparatus for enhanced heat recovery from steam generators and water heaters
35941229	2004	7500437	21	0	Neuco Inc	Method and system for SCR optimization

The forward tracing element of the analysis shows that BTO-funded and Other DOE-funded water heating patents are linked via citations to subsequent patents assigned to a number of very large companies. The influence of BTO-funded and Other DOE-funded water heating research can also be seen across a range of technologies, including electronics and semiconductor manufacturing, gas turbines and solar energy.

Overall, the results from the water heating analysis suggest that DOE-funded patenting in this technology was relatively sparse throughout the time period analyzed. That said, given their relatively small size, the portfolios of DOE-funded (and especially BTO-funded) water heating patents have had a notable influence on subsequent innovations associated with leading companies in this technology. This influence can be seen both over time and across these leading companies, with their innovations related to heat pump water heaters and refrigeration cycles linked via citations to earlier BTO-funded water heating patents. The influence of BTO-funded and Other DOE-funded water heating research can also be seen across a range of other technologies, including electronics and semiconductor manufacturing, gas turbines and solar energy.

7. Conclusions

This report describes the results of an analysis tracing links between building technologies research funded by DOE (BTO plus Other DOE) and subsequent developments both within and beyond these technologies. This tracing is carried out both backwards and forwards in time. The purpose of the backward tracing is to determine the extent to which BTO-funded (and Other DOE-funded) research forms a foundation for the technologies developed by leading building technologies companies. The purpose of the forward tracing is to examine the influence of BTO-funded (and Other DOE-funded) building technologies research upon subsequent developments, both within and outside these technologies. The analysis focuses on three distinct technologies – heating, ventilation and air conditioning (HVAC), appliances, and water heating. Each of these technologies is examined individually, with separate findings for the three technologies.

Overall, the results from the HVAC analysis suggest that DOE-funded patenting in this technology been relatively consistent over time, with BTO-funded patents representing a high percentage of the total. Given their comparatively small size, the portfolios of BTO-funded and Other DOE-funded HVAC patents have had a notable influence on subsequent innovations associated with the leading companies in HVAC technology. The influence of these patents also extends beyond HVAC into other technologies, including advanced materials, solar thermal energy and semiconductor manufacturing.

Meanwhile, the results from the appliances analysis suggest that DOE-funded patenting in this technology also remained relatively consistent throughout the analysis period, with BTO-funded patents representing a high percentage of the total. DOE-funded patents focus primarily on refrigeration technology, while the patents of leading appliance companies have a much broader range, with a particular concentration on washers and dryers. That said, the backward tracing reveals that it is still possible to trace the influence of DOE-funded (and particularly BTO-funded) appliance research on the leading companies, especially in refrigeration and heat exchange technologies. Meanwhile, the forward tracing reveals that much of the influence of BTO-funded and Other DOE-funded appliance research can be seen on subsequent technologies from beyond appliances, notably nanocomposites, advanced materials and energy storage.

Finally, the results from the water heating analysis suggest that DOE-funded patenting in this technology was relatively sparse throughout the time period analyzed. That said, given their relatively small size, the portfolios of DOE-funded (and especially BTO-funded) water heating patents have had a notable influence on subsequent innovations associated with leading companies in this technology. This influence can be seen both over time and across these leading companies, with their innovations related to heat pump water heaters and refrigeration cycles linked via citations to earlier BTO-funded water heating patents. The influence of BTO-funded and Other DOE-funded water heating research can also be seen across a range of other technologies, including electronics and semiconductor manufacturing, gas turbines and solar energy.

Appendix HV-A. BTO-funded HVAC Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Original Assignees	Title
4055964	1976	1977	CONSOLIDATED NATURAL GAS SERVICE CO INC	HEAT PUMP SYSTEM
4178772	1977	1979	CONSOLIDATED NATURAL GAS SERVICE CO INC	HEAT PUMP SYSTEM
4189848	1977	1980	US DEPT OF ENERGY	ENERGY-EFFICIENT REGENERATIVE LIQUID DESICCANT DRYING PROCESS
4205529	1978	1980	US DEPT OF ENERGY	LICL DEHUMIDIFIER LIBR ABSORPTION CHILLER HYBRID AIR CONDITIONING SYSTEM WITH ENERGY RECOVERY
4217765	1979	1980	ATLANTIC RICHFIELD CO	HEAT EXCHANGER-ACCUMULATOR
WO1980002870	1980	1980	ATLANTIC RICHFIELD CO	HEAT PUMP INCLUDING COMPRESSOR HAVING LOW PRESSURE RATIO APPLICATIONS
4262739	1979	1981	US DEPT OF ENERGY	SYSTEM FOR THERMAL ENERGY STORAGE, SPACE HEATING AND COOLING AND POWER CONVERSION
4271681	1979	1981	US DEPT OF ENERGY	LONG-TERM ICE STORAGE FOR COOLING APPLICATIONS
4272268	1977	1981	UNASSIGNED	CHEMICAL HEAT PUMP
EP0030553	1980	1981	ATLANTIC RICHFIELD CO	HEAT PUMP INCLUDING COMPRESSOR HAVING LOW PRESSURE RATIO APPLICATION.
4308723	1979	1982	ATLANTIC RICHFIELD CO	HEAT PUMP EMPLOYING OPTIMAL REFRIGERANT COMPRESSOR FOR LOW PRESSURE RATIO APPLICATIONS
4312188	1979	1982	CONSOLIDATED NATURAL GAS SERVICE CO INC	HEAT PUMP SYSTEM
4337625	1981	1982	BATTELLE DEVELOPMENT CORP	WASTE HEAT DRIVEN ABSORPTION REFRIGERATION PROCESS AND SYSTEM
4347982	1979	1982	ADELPHI RESEARCH CENTER INC	OIL BURNER NOZZLE
4353205	1980	1982	US DEPT OF ENERGY	PRIMARY ZONE AIR PROPORTIONER
WO1982003116	1982	1982	BATTELLE DEVELOPMENT CORP	WASTE HEAT DRIVEN ABSORPTION

				REFRIGERATION PROCESS AND SYSTEM
4375154	1980	1983	UNASSIGNED	AIR HEATING SYSTEM
4377074	1981	1983	KAMAN SCIENCES CORP	ECONOMIZER REFRIGERATION CYCLE SPACE HEATING AND COOLING SYSTEM AND PROCESS
4418538	1980	1983	TRD INC	METHOD AND APPARATUS FOR OPERATING A SELF-STARTING AIR HEATING SYSTEM
EP0073243	1982	1983	BATTELLE DEVELOPMENT CORP	WASTE HEAT DRIVEN ABSORPTION REFRIGERATION PROCESS AND SYSTEM.
RE031281	1979	1983	CONSOLIDATED NATURAL GAS SERVICE CO INC	HEAT PUMP SYSTEM
4424800	1981	1984	US DEPT OF ENERGY	THERMAL CONTROL SYSTEM AND METHOD FOR A PASSIVE SOLAR STORAGE WALL
4449376	1983	1984	WESTINGHOUSE ELECTRIC CORP	INDOOR UNIT FOR ELECTRIC HEAT PUMP
4449377	1983	1984	WESTINGHOUSE ELECTRIC CORP	THERMOSYPHON COIL ARRANGEMENT FOR HEAT PUMP OUTDOOR UNIT
4467623	1983	1984	US DEPT OF ENERGY	COUNTERFLOW ABSORBER FOR AN ABSORPTION REFRIGERATION SYSTEM
4470271	1983	1984	WESTINGHOUSE ELECTRIC CORP	OUTDOOR UNIT CONSTRUCTION FOR AN ELECTRIC HEAT PUMP
4479419	1982	1984	WESTINGHOUSE ELECTRIC CORP	DUAL CAPACITY RECIPROCATING COMPRESSOR
4516916	1982	1985	WESTINGHOUSE ELECTRIC CORP	OIL COOLED, HERMETIC REFRIGERANT COMPRESSOR
4540501	1984	1985	US DEPT OF ENERGY	GAS HYDRATE COOL STORAGE SYSTEM
4542628	1984	1985	US DEPT OF ENERGY	COUPLED DUAL LOOP ABSORPTION HEAT PUMP
4628695	1984	1986	US DEPT OF ENERGY	SOLID STATE RADIATIVE HEAT PUMP
4635469	1985	1987	UNASSIGNED	METHODS AND APPARATUS FOR MEASURING THE TIGHTNESS OF ENCLOSURES
4727722	1987	1988	US DEPT OF ENERGY	ROTARY MAGNETIC HEAT PUMP
4732008	1986	1988	US DEPT OF ENERGY	TRIPLE EFFECT ABSORPTION CHILLER

				UTILIZING TWO REFRIGERATION CIRCUITS
4825939	1986	1989	UNIVERSITY OF DAYTON	POLYMERIC COMPOSITIONS INCORPORATING POLYETHYLENE GLYCOL AS A PHASE CHANGE MATERIAL
4827728	1988	1989	MARTIN MARIETTA ENERGY SYSTEMS INC	SEVEN-EFFECT ABSORPTION REFRIGERATION
4912929	1989	1990	SUN POWER INC	VARIABLE GAS SPRING FOR MATCHING POWER OUTPUT FROM FPSE TO LOAD OF REFRIGERANT COMPRESSOR
4921515	1988	1990	UNASSIGNED	ADVANCED REGENERATIVE ABSORPTION REFRIGERATION CYCLES
4934149	1989	1990	US DEPT OF ENERGY	METHOD OF REDUCING CHLOROFLUOROCARBON REFRIGERANT EMISSONS TO THE ATMOSPHERE
5020977	1989	1991	UNASSIGNED	STANDING WAVE COMPRESSOR
5056588	1990	1991	INSTATHERM CO	EVAPORATIVE COOLING ENHANCED COLD STORAGE SYSTEM
WO1991002149	1990	1991	SUN POWER INC	VARIABLE GAS SPRING FOR MATCHING POWER OUTPUT FROM FPSE TO LOAD OF REFRIGERANT COMPRESSOR
WO1991019867	1991	1991	MIDWEST RESEARCH INSTITUTE	IMPROVED COMPACT VACUUM INSULATION
5107649	1990	1992	MIDWEST RESEARCH INSTITUTE	COMPACT VACUUM INSULATION EMBODIMENTS
5126721	1990	1992	US DEPT OF ENERGY	FLAME QUALITY MONITOR SYSTEM FOR FIXED FIRING RATE OIL BURNERS
5157893	1990	1992	MIDWEST RESEARCH INSTITUTE	COMPACT VACUUM INSULATION
EP0508608	1992	1992	PHILLIPS ENGINEERING CO	HIGH EFFICIENCY ABSORPTION CYCLE OF THE GENERATOR-ABSORBER HEAT-EXCHANGE TYPE.
5175975	1992	1993	MIDWEST RESEARCH INSTITUTE	COMPACT VACUUM INSULATION
5184015	1991	1993	MARTIN MARIETTA ENERGY SYSTEMS INC	CHARGED PARTICLE MOBILITY REFRIGERANT ANALYZER
5245833	1992	1993	MARTIN MARIETTA	LIQUID OVER-FEEDING

			ENERGY SYSTEMS INC	AIR CONDITIONING SYSTEM AND METHOD
5271235	1991	1993	PHILLIPS ENGINEERING CO	HIGH EFFICIENCY ABSORPTION CYCLE OF THE GAX TYPE
5273106	1992	1993	MECHANICAL TECHNOLOGY INC	SELF-DEFROSTING RECUPERATIVE AIR-TO-AIR HEAT EXCHANGER
EP0535147	1991	1993	MIDWEST RESEARCH INSTITUTE	IMPROVED COMPACT VACUUM INSULATION.
5338254	1992	1994	MIDWEST RESEARCH INSTITUTE	INCREASING JET ENTRAINMENT, MIXING AND SPREADING
5339890	1993	1994	CLIMATE MASTER INC	GROUND SOURCE HEAT PUMP SYSTEM COMPRISING MODULAR SUBTERRANEAN HEAT EXCHANGE UNITS WITH CONCENTRIC CONDUITS
5360056	1993	1994	MARTIN MARIETTA ENERGY SYSTEMS INC	TEMPERATURE INITIATED PASSIVE COOLING SYSTEM
5367884	1993	1994	PHILLIPS ENGINEERING CO	GENERATOR-ABSORBER-HEAT EXCHANGE HEAT TRANSFER APPARATUS AND METHOD AND USE THEREOF IN A HEAT PUMP
5372016	1993	1994	CLIMATE MASTER INC	GROUND SOURCE HEAT PUMP SYSTEM COMPRISING MODULAR SUBTERRANEAN HEAT EXCHANGE UNITS WITH MULTIPLE PARALLEL SECONDARY CONDUITS
WO1994015154	1993	1994	MIDWEST RESEARCH INSTITUTE	INCREASING JET ENTRAINMENT, MIXING AND SPREADING
WO1994018510	1994	1994	CLIMATE MASTER INC	GROUND SOURCE HEAT PUMP SYSTEM COMPRISING MODULAR SUBTERRANEAN HEAT EXCHANGE UNITS WITH MULTIPLE PARALLEL SECONDARY CONDUITS
WO1994029655	1994	1994	PHILLIPS ENGINEERING CO	GENERATOR-ABSORBER-HEAT EXCHANGE HEAT TRANSFER APPARATUS AND METHOD AND USE THEREOF IN A HEAT PUMP
5392606	1994	1995	MARTIN MARIETTA ENERGY SYSTEMS INC	SELF-CONTAINED SMALL UTILITY SYSTEM
5447032	1994	1995	UNIVERSITY OF CALIFORNIA	FLUORESCENT REFRIGERATION
5477914	1994	1995	CLIMATE MASTER INC	GROUND SOURCE HEAT PUMP SYSTEM

				COMPRISING MODULAR SUBTERRANEAN HEAT EXCHANGE UNITS WITH MULTIPLE PARALLEL SECONDARY CONDUITS
EP0681676	1994	1995	CLIMATE MASTER INC	GROUND SOURCE HEAT PUMP SYSTEM COMPRISING MODULAR SUBTERRANEAN HEAT EXCHANGE UNITS WITH MULTIPLE PARALLEL SECONDARY CONDUITS.
5501268	1993	1996	MARTIN MARIETTA ENERGY SYSTEMS INC	METHOD OF ENERGY LOAD MANAGEMENT USING PCM FOR HEATING AND COOLING OF BUILDINGS
5522930	1994	1996	UNIVERSITY OF CALIFORNIA	METHOD AND DEVICE FOR PRODUCING AND DELIVERING AN AEROSOL FOR REMOTE SEALING AND COATING
5533355	1994	1996	CLIMATE MASTER INC	SUBTERRANEAN HEAT EXCHANGE UNITS COMPRISING MULTIPLE SECONDARY CONDUITS AND MULTI-TIERED INLET AND OUTLET MANIFOLDS
5570584	1994	1996	PHILLIPS ENGINEERING CO	GENERATOR-ABSORBER-HEAT EXCHANGE HEAT TRANSFER APPARATUS AND METHOD AND USE THEREOF IN A HEAT PUMP
5579652	1994	1996	PHILLIPS ENGINEERING CO	GENERATOR-ABSORBER-HEAT EXCHANGE HEAT TRANSFER APPARATUS AND METHOD AND USE THEREOF IN A HEAT PUMP
EP0702773	1994	1996	PHILLIPS ENGINEERING CO	GENERATOR-ABSORBER-HEAT EXCHANGE HEAT TRANSFER APPARATUS AND METHOD AND USE THEREOF IN A HEAT PUMP
EP0725919	1995	1996	PHILLIPS ENGINEERING CO	GENERATOR-ABSORBER-HEAT EXCHANGE HEAT TRANSFER APPARATUS AND METHOD AND USE THEREOF IN A HEAT PUMP
EP0739471	1995	1996	PHILLIPS ENGINEERING CO	GENERATOR-ABSORBER HEAT EXCHANGE HEAT TRANSFER APPARATUS AND METHOD USING AN INTERMEDIATE LIQUOR AND USE THEREOF IN AN ABSORPTION HEAT PUMP
WO1996007062	1995	1996	PHILLIPS	GENERATOR-ABSORBER-

			ENGINEERING CO	HEAT EXCHANGE HEAT TRANSFER APPARATUS AND METHOD AND USE THEREOF IN A HEAT PUMP
WO1996014166	1995	1996	UNIVERSITY OF CALIFORNIA	A METHOD AND DEVICE FOR PRODUCING AND DELIVERING AN AEROSOL FOR REMOTE SEALING AND COATING
WO1996014544	1995	1996	CLIMATE MASTER INC	SUBTERRANEAN HEAT EXCHANGE UNITS COMPRISING MULTIPLE SECONDARY CONDUITS AND MULTI-TIERED INLET AND OUTLET MANIFOLDS
WO1996016303	1995	1996	PHILLIPS ENGINEERING CO	GENERATOR-ABSORBER HEAT EXCHANGE HEAT TRANSFER APPARATUS AND METHOD USING AN INTERMEDIATE LIQUOR AND USE THEREOF IN AN ABSORPTION HEAT PUMP
5591690	1994	1997	MIDWEST RESEARCH INSTITUTE	SELF ASSEMBLED MOLECULAR MONOLAYERS ON HIGH SURFACE AREA MATERIALS AS MOLECULAR GETTERS
5628200	1995	1997	WALLACE HEATING & AIR CONDITIONING INC	HEAT PUMP SYSTEM WITH SELECTIVE SPACE COOLING
EP0793543	1995	1997	UNIVERSITY OF CALIFORNIA	A METHOD AND DEVICE FOR PRODUCING AND DELIVERING AN AEROSOL FOR REMOTE SEALING AND COATING
WO1997041396	1997	1997	PHILLIPS ENGINEERING CO	GENERATOR-ABSORBER-HEAT EXCHANGE HEAT TRANSFER APPARATUS AND METHOD AND USE THEREOF IN A HEAT PUMP
5782097	1996	1998	PHILLIPS ENGINEERING CO	GENERATOR-ABSORBER-HEAT EXCHANGE HEAT TRANSFER APPARATUS AND METHOD AND USE THEREOF IN A HEAT PUMP
5811026	1996	1998	PHILLIPS ENGINEERING CO	CORROSION INHIBITOR FOR AQUEOUS AMMONIA ABSORPTION SYSTEM
5845502	1996	1998	LOCKHEED MARTIN ENERGY RESEARCH CORP	HEAT PUMP HAVING IMPROVED DEFROST SYSTEM
5875607	1997	1999	US DEPT OF ENERGY	LOW-COST EXTERIOR INSULATION PROCESS AND STRUCTURE
5976471	1997	1999	LOCKHEED MARTIN	OZONE DECOMPOSING

			ENERGY RESEARCH CORP	FILTER
5980984	1997	1999	UNIVERSITY OF CALIFORNIA	METHOD FOR SEALING REMOTE LEAKS IN AN ENCLOSURE USING AN AEROSOL
EP0897516	1997	1999	PHILLIPS ENGINEERING CO	GENERATOR-ABSORBER-HEAT EXCHANGE HEAT TRANSFER APPARATUS AND METHOD AND USE THEREOF IN A HEAT PUMP
WO1999042768	1998	1999	LOCKHEED MARTIN ENERGY RESEARCH CORP	HEAT PUMP HAVING IMPROVED DEFROST SYSTEM
WO1999064223	1999	1999	LOCKHEED MARTIN ENERGY RESEARCH CORP	PITCH-BASED CARBON FOAM HEAT SINK WITH PHASE CHANGE MATERIAL
6037032	1998	2000	LOCKHEED MARTIN ENERGY RESEARCH CORP	PITCH-BASED CARBON FOAM HEAT SINK WITH PHASE CHANGE MATERIAL
6105335	1998	2000	US DEPT OF ENERGY	SUSTAINABLE WALL CONSTRUCTION AND EXTERIOR INSULATION RETROFIT TECHNOLOGY PROCESS AND STRUCTURE
6116330	1999	2000	UNIVERSITY OF DAYTON	HEAT STORAGE SYSTEM UTILIZING PHASE CHANGE MATERIALS GOVERNMENT RIGHTS
WO2000079203	2000	2000	UNIVERSITY OF DAYTON	HEAT STORAGE SYSTEM UTILIZING PHASE CHANGE MATERIALS
6257011	1999	2001	UT-BATTELLE LLC	PERSONAL COOLING APPARATUS AND METHOD
6276155	2000	2001	UT-BATTELLE LLC	PERSONAL COOLING APPARATUS AND METHOD
6295648	2000	2001	UT-BATTELLE LLC	PERSONAL COOLING APPARATUS AND METHOD
6378605	1999	2002	MIDWEST RESEARCH INSTITUTE	HEAT EXCHANGER WITH TRANSPIRED, HIGHLY POROUS FINS
6399149	2000	2002	UT-BATTELLE LLC	PITCH-BASED CARBON FOAM HEAT SINK WITH PHASE CHANGE MATERIAL
6430935	2001	2002	UT-BATTELLE LLC	PERSONAL COOLING AIR FILTERING DEVICE
6467284	2001	2002	UT-BATTELLE LLC	FROSTLESS HEAT PUMP HAVING THERMAL EXPANSION VALVES
EP1165457	1999	2002	UT-BATTELLE LLC	PITCH-BASED CARBON FOAM HEAT SINK WITH PHASE CHANGE

				MATERIAL
WO2002001132	2001	2002	AIL RESEARCH INC	HEAT EXCHANGE ASSEMBLY
WO2002041095	2001	2002	BECHTEL BWXT IDAHO LLC	MONITORING AND ADJUSTING INDOOR AIR QUALITY
6568466	2001	2003	UNASSIGNED	HEAT EXCHANGE ASSEMBLY
6592449	2002	2003	INTERNATIONAL BUSINESS MACHINES CORP	SMART FAN MODULES AND SYSTEM
EP1299681	2001	2003	AIL RESEARCH INC	HEAT EXCHANGE ASSEMBLY
WO2003018336	2002	2003	UT-BATTELLE LLC	PERSONAL COOLING AIR FILTERING DEVICE
WO2003047761	2002	2003	UNIVERSITY OF CALIFORNIA	METHOD AND APPARATUS FOR DUCT SEALING USING A CLOG-RESISTANT INSERTABLE INJECTOR
6711470	2000	2004	BECHTEL BWXT IDAHO LLC	METHOD, SYSTEM AND APPARATUS FOR MONITORING AND ADJUSTING THE QUALITY OF INDOOR AIR
6745826	2003	2004	AIL RESEARCH INC	HEAT EXCHANGE ASSEMBLY
6751964	2002	2004	SEMCO INSTR INC	DESICCANT-BASED DEHUMIDIFICATION SYSTEM AND METHOD
6763671	2003	2004	UT-BATTELLE LLC	PERSONAL, CLOSED-CYCLE COOLING AND PROTECTIVE APPARATUS AND THERMAL BATTERY THEREFOR
6778945	2001	2004	BATTELLE MEMORIAL INSTITUTE	ROOFTOP PACKAGE UNIT DIAGNOSTICIAN
6791836	2003	2004	INTERNATIONAL BUSINESS MACHINES CORP	SMART FAN MODULES AND SYSTEM
EP1450962	2002	2004	UNIVERSITY OF CALIFORNIA	METHOD AND APPARATUS FOR DUCT SEALING USING A CLOG-RESISTANT INSERTABLE INJECTOR
WO2004003439	2003	2004	SEMCO INSTR INC	DESICCANT-BASED DEHUMIDIFICATION SYSTEM AND METHOD
6845629	2003	2005	DAVIS ENERGY GROUP INC	VERTICAL COUNTERFLOW EVAPORATIVE COOLER
6848265	2003	2005	AIL RESEARCH INC	AIR CONDITIONING SYSTEM
6868678	2002	2005	UT-BATTELLE LLC	NON-INTRUSIVE REFRIGERANT CHARGE INDICATOR
EP1527304	2003	2005	SEMCO INSTR INC	DESICCANT-BASED DEHUMIDIFICATION

				SYSTEM AND METHOD
WO2005096786	2005	2005	AIL RESEARCH INC	HEAT AND MASS EXCHANGER
6993924	2004	2006	UT-BATTELLE LLC	FLOATING LOOP SYSTEM FOR COOLING INTEGRATED MOTORS AND INVERTERS USING HOT LIQUID REFRIGERANT
7016742	2002	2006	BATTELLE DEVELOPMENT CORP	DECISION SUPPORT FOR OPERATIONS AND MAINTENANCE (DSOM) SYSTEM
7156320	2002	2007	UNIVERSITY OF CALIFORNIA	METHOD AND APPARATUS FOR DUCT SEALING USING A CLOG-RESISTANT INSERTABLE INJECTOR
7191605	2005	2007	UT-BATTELLE LLC	FLOATING LOOP METHOD FOR COOLING INTEGRATED MOTORS AND INVERTERS USING HOT LIQUID REFRIGERANT
7246997	2003	2007	GENERAL ELECTRIC CO	INTEGRATED HIGH EFFICIENCY BLOWER APPARATUS FOR HVAC SYSTEMS
7269966	2005	2007	AIL RESEARCH INC	HEAT AND MASS EXCHANGER
EP1751479	2005	2007	AIL RESEARCH INC	HEAT AND MASS EXCHANGER
7322205	2004	2008	DAVIS ENERGY GROUP INC	HYDRONIC ROOFTOP COOLING SYSTEMS
WO2009094032	2008	2009	ALLIANCE FOR SUSTAINABLE ENERGY LLC	INDIRECT EVAPORATIVE COOLER USING MEMBRANE-CONTAINED, LIQUID DESICCANT FOR DEHUMIDIFICATION
7757508	2005	2010	UT-BATTELLE LLC	SUPER ENERGY SAVER HEAT PUMP WITH DYNAMIC HYBRID PHASE CHANGE MATERIAL
7851017	2006	2010	UNIVERSITY OF CALIFORNIA	METHOD AND APPARATUS FOR DUCT SEALING USING A CLOG-RESISTANT INSERTABLE INJECTOR
EP2250446	2008	2010	ALLIANCE FOR SUSTAINABLE ENERGY LLC	INDIRECT EVAPORATIVE COOLER
WO2010002957	2009	2010	CARRIER CORP	ENERGY RECOVERY VENTILATOR
7966841	2007	2011	AIL RESEARCH INC	HEAT AND MASS EXCHANGER
8011598	2009	2011	DELPHI TECHNOLOGIES INC	SOFC POWER SYSTEM WITH A/C SYSTEM AND HEAT PUMP FOR

				STATIONARY AND TRANSPORTATION APPLICATIONS
EP2302305	2010	2011	DELPHI TECHNOLOGIES INC	SOFC POWER SYSTEM WITH A/C SYSTEM AND HEAT PUMP FOR STATIONARY AND TRANSPORTATION APPLICATIONS
WO2011034594	2010	2011	UNASSIGNED	FLOW-SYNCHRONOUS FIELD MOTION REFRIGERATION
WO2011106069	2010	2011	GENERAL ELECTRIC CO	LIGHTING SYSTEM WITH THERMAL MANAGEMENT SYSTEM
WO2012118982	2012	2012	SANDIA CORP	AXIAL FLOW HEAT EXCHANGER DEVICES AND METHODS FOR HEAT TRANSFER USING AXIAL FLOW DEVICES
WO2012170887	2012	2012	AIL RESEARCH INC	HEAT AND MASS EXCHANGERS HAVING EXTRUDED PLATES
8434906	2010	2013	GENERAL ELECTRIC CO	LIGHTING SYSTEM WITH THERMAL MANAGEMENT SYSTEM
EP2539634	2010	2013	GENERAL ELECTRIC CO	LIGHTING SYSTEM WITH THERMAL MANAGEMENT SYSTEM
WO2013130311	2013	2013	SIEMENS CORP	SYSTEM AND METHOD OF TOTAL COST OPTIMIZATION FOR BUILDINGS WITH HYBRID VENTILATION
WO2013133967	2013	2013	SIEMENS CORP	SYSTEM AND METHOD OF CONTROLLING ENERGY CONSUMPTION IN A BUILDING BASED ON OCCUPANCY DATA, WEATHER DATA AND ENERGY PRICE DATA
WO2013155258	2013	2013	THERMOLIFT INC	HEAT PUMP WITH ELECTOMECHANICALLY-ACTUATED DISPLACERS
8769971	2008	2014	ALLIANCE FOR SUSTAINABLE ENERGY LLC	INDIRECT EVAPORATIVE COOLER USING MEMBRANE-CONTAINED, LIQUID DESICCANT FOR DEHUMIDIFICATION
8843238	2011	2014	JOHNSON CONTROLS TECHNOLOGY CO	SYSTEMS AND METHODS FOR CONTROLLING ENERGY USE IN A BUILDING MANAGEMENT SYSTEM USING ENERGY BUDGETS
EP2772706	2014	2014	WHIRLPOOL CORP	REFRIGERATION SYSTEM

				HAVING DUAL SUCTION PORT COMPRESSOR
WO2014059123	2013	2014	SIEMENS CORP	ON-LINE OPTIMIZATION SCHEME FOR HVAC DEMAND RESPONSE
8960972	2013	2015	GENERAL ELECTRIC CO	LIGHTING SYSTEM WITH THERMAL MANAGEMENT SYSTEM
9032731	2011	2015	WILLIAM MARSH RICE UNIVERSITY	COOLING SYSTEMS AND HYBRID A/C SYSTEMS USING AN ELECTROMAGNETIC RADIATION-ABSORBING COMPLEX
9062890	2009	2015	CARRIER CORP	ENERGY RECOVERY VENTILATOR
9119246	2014	2015	GENERAL ELECTRIC CO	LIGHTING SYSTEM WITH THERMAL MANAGEMENT SYSTEM
9119247	2014	2015	GENERAL ELECTRIC CO	LIGHTING SYSTEM WITH THERMAL MANAGEMENT SYSTEM
9140460	2013	2015	ALLIANCE FOR SUSTAINABLE ENERGY LLC	CONTROL METHODS AND SYSTEMS FOR INDIRECT EVAPORATIVE COOLERS
9140471	2013	2015	ALLIANCE FOR SUSTAINABLE ENERGY LLC	INDIRECT EVAPORATIVE COOLERS WITH ENHANCED HEAT TRANSFER
9207001	2012	2015	MAINSTREAM ENGINEERING CORP	RETROFIT DEVICE TO IMPROVE VAPOR COMPRESSION COOLING SYSTEM PERFORMANCE BY DYNAMIC BLOWER SPEED MODULATION
EP2836772	2013	2015	THERMOLIFT INC	HEAT PUMP WITH ELECTOMECHANICALLY-ACTUATED DISPLACERS
EP2941598	2013	2015	SIEMENS CORP	ON-LINE OPTIMIZATION SCHEME FOR HVAC DEMAND RESPONSE
WO2015057297	2014	2015	CARRIER CORP	OPERATION OF A CASCADE AIR CONDITIONING SYSTEM WITH TWO-PHASE LOOP
WO2015077214	2014	2015	THERMOLIFT INC	A FOUR-PROCESS CYCLE FOR A VUILLEUMIER HEAT PUMP
9228762	2013	2016	WHIRLPOOL CORP	REFRIGERATION SYSTEM HAVING DUAL SUCTION PORT COMPRESSOR
9261100	2012	2016	SANDIA CORP	AXIAL FLOW HEAT EXCHANGER DEVICES AND METHODS FOR HEAT TRANSFER USING AXIAL FLOW DEVICES

9322566	2014	2016	JOHNSON CONTROLS TECHNOLOGY CO	SYSTEMS AND METHODS FOR CONTROLLING ENERGY USE DURING A DEMAND LIMITING PERIOD
9389025	2012	2016	AIL RESEARCH INC	HEAT AND MASS EXCHANGERS HAVING EXTRUDED PLATES
9417005	2012	2016	MAINSTREAM ENGINEERING CORP	RETROFIT DEVICE AND METHOD TO IMPROVE HUMIDITY CONTROL OF VAPOR COMPRESSION COOLING SYSTEMS
9468047	2014	2016	GENERAL ELECTRIC CO	LIGHTING SYSTEM WITH THERMAL MANAGEMENT SYSTEM
9518784	2014	2016	ALLIANCE FOR SUSTAINABLE ENERGY LLC	INDIRECT EVAPORATIVE COOLER USING MEMBRANE-CONTAINED, LIQUID DESICCANT FOR DEHUMIDIFICATION
EP3058287	2014	2016	CARRIER CORP	OPERATION OF A CASCADE AIR CONDITIONING SYSTEM WITH TWO-PHASE LOOP
EP3084319	2014	2016	THERMOLIFT INC	A FOUR-PROCESS CYCLE FOR A VUILLEUMIER HEAT PUMP
9677794	2013	2017	THERMOLIFT INC	HEAT PUMP WITH ELECTROMECHANICALLY-ACTUATED DISPLACERS
9726410	2015	2017	UT-BATTELLE LLC	PORTABLE REFRIGERANT CHARGE METER AND METHOD FOR DETERMINING THE ACTUAL REFRIGERANT CHARGE IN HVAC SYSTEMS
9739510	2010	2017	UNASSIGNED	FLOW-SYNCHRONOUS FIELD MOTION REFRIGERATION
9746208	2015	2017	WHIRLPOOL CORP	COOLING SYSTEM HAVING DUAL SUCTION PORT COMPRESSOR
9874885	2011	2018	HONEYWELL INTERNATIONAL INC	SYSTEM AND METHOD FOR OPTIMAL LOAD AND SOURCE SCHEDULING IN CONTEXT AWARE HOMES
9892472	2013	2018	SIEMENS CORP	COST OPTIMIZATION FOR BUILDINGS WITH HYBRID VENTILATION SYSTEMS
9982920	2014	2018	CARRIER CORP	OPERATION OF A CASCADE AIR CONDITIONING SYSTEM WITH TWO-PHASE LOOP
10024590	2017	2018	XERGY INC	ELECTROCHEMICAL

				COMPRESSOR REFRIGERATION APPARTUS WITH INTEGRAL LEAK DETECTION SYSTEM
10030893	2014	2018	THERMOLIFT INC	FOUR-PROCESS CYCLE FOR A VUILLEUMIER HEAT PUMP
10036581	2014	2018	NATIONAL TECHNOLOGY & ENGINEERING SOLUTIONS OF SANDIA LLC	HEAT TRANSFER ASSEMBLIES, SYSTEMS, AND METHODS FOR CONDITIONING A MEDIUM
10041701	2014	2018	NATIONAL TECHNOLOGY & ENGINEERING SOLUTIONS OF SANDIA LLC	HEATING AND COOLING DEVICES, SYSTEMS AND RELATED METHOD
10060681	2016	2018	UNIVERSITY OF LOUISVILLE	HEAT PIPE AUGMENTED PASSIVE SOLAR HEATING SYSTEM
10077915	2013	2018	SIEMENS CORP	ON-LINE OPTIMIZATION SCHEME FOR HVAC DEMAND RESPONSE
10095207	2013	2018	SIEMENS CORP	SYSTEM AND METHOD OF ENERGY MANAGEMENT CONTROL
10132574	2016	2018	SANDIA CORP	AXIAL FLOW HEAT EXCHANGER DEVICES AND METHODS FOR HEAT TRANSFER USING AXIAL FLOW DEVICES
10254721	2016	2019	JOHNSON CONTROLS TECHNOLOGY CO	CASCADED SYSTEMS AND METHODS FOR CONTROLLING ENERGY USE DURING A DEMAND LIMITING PERIOD
10352595	2017	2019	UNASSIGNED	SYSTEMS AND METHODS FOR FLOW-SYNCHRONOUS FIELD MOTION HEAT TRANSFER
10545518	2017	2020	ADEMCO INC	SYSTEM AND METHOD FOR OPTIMAL LOAD AND SOURCE SCHEDULING IN CONTEXT AWARE HOMES

Appendix HV-B. Other DOE-funded HVAC Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Original Assignees	Title
4176523	1978	1979	GARRETT CORP	ADSORPTION AIR CONDITIONER
4182398	1977	1980	US DEPT OF ENERGY	CROSSLINKED CRYSTALLINE POLYMER AND METHODS FOR COOLING AND HEATING
4224803	1978	1980	UNASSIGNED	CHEMICAL HEAT PUMP
4280333	1979	1981	US DEPT OF ENERGY	PASSIVE ENVIRONMENTAL TEMPERATURE CONTROL SYSTEM
4307578	1980	1981	ATLANTIC RICHFIELD CO	HEAT EXCHANGER EFFICIENTLY OPERABLE ALTERNATIVELY AS EVAPORATOR OR CONDENSER
4308042	1980	1981	ATLANTIC RICHFIELD CO	HEAT PUMP WITH FREEZE-UP PREVENTION
4313424	1980	1982	US DEPT OF ENERGY	SOLAR HEATING SYSTEM
4336692	1980	1982	ATLANTIC RICHFIELD CO	DUAL SOURCE HEAT PUMP
4355522	1980	1982	US DEPT OF ENERGY	PASSIVE ICE FREEZING-RELEASING HEAT PIPE
4372376	1980	1983	US DEPT OF ENERGY	HEAT PUMP APPARATUS
4380156	1981	1983	ATLANTIC RICHFIELD CO	MULTIPLE SOURCE HEAT PUMP
4425903	1981	1984	UNASSIGNED	CHEMICAL HEAT PUMP
4429684	1981	1984	UNASSIGNED	CHEMICAL HEAT PUMP
4441484	1981	1984	UNASSIGNED	CHEMICAL HEAT PUMP
4532778	1981	1985	ROCKET RESEARCH CORP	CHEMICAL HEAT PUMP AND CHEMICAL ENERGY STORAGE SYSTEM
4556049	1981	1985	UNASSIGNED	INTEGRATED SOLAR COLLECTOR
4584842	1979	1986	UNASSIGNED	SOLAR REFRIGERATION
4624113	1985	1986	US DEPT OF ENERGY	PASSIVE-SOLAR DIRECTIONAL-RADIATING COOLING SYSTEM
5014680	1989	1991	US DEPT OF ENERGY	SELF-POWERED AUTOMATIC SECONDARY AIR CONTROLLERS FOR WOODSTOVES AND SMALL FURNACES
5462610	1993	1995	IOWA STATE UNIVERSITY	LANTHANIDE AL-NI BASE ERICSSON CYCLE MAGNETIC REFRIGERANTS
5816062	1997	1998	YU FENG ENTERPRISE CO LTD	AIR CONDITIONING SYSTEM WITH SUPPLEMENTAL ICE STORING AND COOLING CAPACITY

5848532	1997	1998	AMERICAN SUPERCONDUCTOR CORP	COOLING SYSTEM FOR SUPERCONDUCTING MAGNET
WO1998048224	1998	1998	AMERICAN SUPERCONDUCTOR CORP	COOLING SYSTEM FOR SUPERCONDUCTING MAGNET
EP1000304	1998	2000	AMERICAN SUPERCONDUCTOR CORP	COOLING SYSTEM FOR SUPERCONDUCTING MAGNET
6193601	1998	2001	SANDIA CORP	MODULE BAY WITH DIRECTED FLOW
6220521	1999	2001	CATERPILLAR INC	VEHICLE HYDRAULIC SYSTEM THAT PROVIDES HEAT FOR PASSENGER COMPARTMENT
6230503	1999	2001	SANDIA CORP	METHOD AND APPARATUS FOR EXTRACTING WATER FROM AIR
6244052	2000	2001	UNIVERSITY OF CHICAGO	METHOD AND APPARATUS FOR PRODUCING PHASE CHANGE ICE PARTICULATE PERFLUOROCARBON SLURRIES
WO2001008464	2000	2001	UNIVERSITY OF CHICAGO	METHOD AND APPARATUS FOR PRODUCING PHASE CHANGE ICE PARTICULATE PERFLUOROCARBON SLURRIES
WO2001009558	2000	2001	UNIVERSITY OF CHICAGO	METHODS AND APPARATUS FOR PRODUCING PHASE CHANGE ICE PARTICULATE SALINE SLURRIES
WO2001036885	2000	2001	SANDIA CORP	METHOD AND APPARATUS FOR EXTRACTING WATER FROM AIR
6360549	2001	2002	SANDIA CORP	METHOD AND APPARATUS FOR EXTRACTING WATER FROM AIR
6413444	2000	2002	UNIVERSITY OF CHICAGO	METHODS AND APPARATUS FOR PRODUCING PHASE CHANGE ICE PARTICULATE SALINE SLURRIES
6453684	2001	2002	SANDIA CORP	METHOD AND APPARATUS FOR EXTRACTING WATER FROM AIR
EP1208338	2000	2002	UNIVERSITY OF CHICAGO	METHODS AND APPARATUS FOR PRODUCING PHASE CHANGE ICE PARTICULATE SALINE SLURRIES
6511525	2001	2003	SANDIA CORP	METHOD AND APPARATUS FOR EXTRACTING WATER FROM AIR USING A DESICCANT
6530240	2001	2003	GAS TECHNOLOGY INSTITUTE	CONTROL METHOD FOR MIXED REFRIGERANT BASED NATURAL GAS

				LIQUEFIER
6604575	2002	2003	SOUTHEASTERN UNIVER RESEARCH ASSN INC	HEAT EXCHANGE APPARATUS
6629412	2002	2003	UT-BATTELLE LLC	ELECTRICITY-PRODUCING HEATING APPARATUS UTILIZING A TURBINE GENERATOR IN A SEMI-CLOSED BRAYTON CYCLE
WO2003050459	2002	2003	GAS TECHNOLOGY INSTITUTE	CONTROL METHOD FOR MIXED REFRIGERANT BASED NATURAL GAS LIQUEFIER
6687640	2001	2004	SANDIA CORP	AIRBORNE AGENT CONCENTRATION ANALYSIS
6780505	2000	2004	UT-BATTELLE LLC	PITCH-BASED CARBON FOAM HEAT SINK WITH PHASE CHANGE MATERIAL
EP1456589	2002	2004	GAS TECHNOLOGY INSTITUTE	CONTROL METHOD FOR MIXED REFRIGERANT BASED NATURAL GAS LIQUEFIER
WO2004050400	2003	2004	CATERPILLAR INC	SYSTEM FOR HEATING THE CABIN OF A WORK MACHINE BY USING RESIDUAL HEAT
6874695	2002	2005	CATERPILLAR INC	CONTROL SYSTEM FOR, AND A METHOD OF, HEATING AN OPERATOR STATION OF A WORK MACHINE
6880344	2003	2005	UTC POWER LLC	COMBINED RANKINE AND VAPOR COMPRESSION CYCLES
6964294	2003	2005	MIDWEST RESEARCH INSTITUTE	PASSIVE COOLING SYSTEM FOR A VEHICLE
7014151	2002	2006	UT-BATTELLE LLC	PITCH-BASED CARBON FOAM HEAT SINK WITH PHASE CHANGE MATERIAL
7157019	2002	2007	UT-BATTELLE LLC	PITCH-BASED CARBON FOAM HEAT SINK WITH PHASE CHANGE MATERIAL
7166237	2002	2007	UT-BATTELLE LLC	PITCH-BASED CARBON FOAM HEAT SINK WITH PHASE CHANGE MATERIAL
7189158	2004	2007	CATERPILLAR INC	AIRFLOW CONTROL SYSTEM
WO2011014508	2010	2011	PENN STATE UNIVERSITY	REFRIGERATION DEVICES BASED ON POLAR-POPYMERS
WO2012019022	2011	2012	UNIVERSITY OF CALIFORNIA	SYSTEMS AND METHODS FOR ANALYZING BUILDING OPERATIONS SENSOR DATA
8613204	2010	2013	LAWRENCE	SOLAR-POWERED COOLING

			LIVERMORE NATIONAL SECURITY LLC	SYSTEM
EP2601560	2011	2013	UNIVERSITY OF CALIFORNIA	SYSTEMS AND METHODS FOR ANALYZING BUILDING OPERATIONS SENSOR DATA
WO2013122674	2012	2013	UNITED TECHNOLOGIES CORP	EVAPORATIVE COOLER INCLUDING ONE OR MORE ROTATING COOLER LOUVRES
8720209	2011	2014	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	SOLID STATE RAPID THERMOCYCLING
8869542	2010	2014	PENN STATE UNIVERSITY	POLYMER-BASED ELECTROCALORIC COOLING DEVICES
EP2777799	2014	2014	CARRIER CORP	MEMBRANE CONTACTOR FOR DEHUMIDIFICATION SYSTEMS
EP2781251	2014	2014	CARRIER CORP	MEMBRANE CONTACTOR FOR DEHUMIDIFICATION SYSTEMS
WO2014015099	2013	2014	INTERNATIONAL BUSINESS MACHINES CORP	DATA CENTER COOLING SYSTEM
8943851	2012	2015	UNITED TECHNOLOGIES CORP	EVAPORATIVE COOLER INCLUDING ONE OR MORE ROTATING COOLER LOUVERS
8949040	2011	2015	INTERNATIONAL BUSINESS MACHINES CORP	METHODS AND APPARATUS FOR MANAGING CORROSION IN BUILDINGS
8978401	2012	2015	INTERNATIONAL BUSINESS MACHINES CORP	DATA CENTER COOLING SYSTEM
9043163	2011	2015	UNIVERSITY OF CALIFORNIA	SYSTEMS AND METHODS FOR ANALYZING BUILDING OPERATIONS SENSOR DATA
9091466	2013	2015	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	SOLAR-POWERED COOLING SYSTEM
9107327	2012	2015	INTERNATIONAL BUSINESS MACHINES CORP	DATA CENTER COOLING METHOD
9170028	2011	2015	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	METHODS AND COMPOSITIONS FOR RAPID THERMAL CYCLING
9273876	2014	2016	CARRIER CORP	MEMBRANE CONTACTOR FOR DEHUMIDIFICATION SYSTEMS
9308491	2014	2016	CARRIER CORP	MEMBRANE CONTACTOR FOR DEHUMIDIFICATION SYSTEMS

WO2016018451	2014	2016	ASTRONAUTICS CORP OF AMERICA	MAGNETIC REFRIGERATION SYSTEM WITH SEPARATED INLET AND OUTLET FLOW
WO2016043792	2014	2016	ASTRONAUTICS CORP OF AMERICA	MAGNETIC REFRIGERATION SYSTEM WITH UNEQUAL BLOWS
WO2016183281	2016	2016	ALLIANCE FOR SUSTAINABLE ENERGY LLC	SPLIT HEATING AND COOLING SYSTEMS
9677792	2014	2017	ASTRONAUTICS CORP OF AMERICA	MAGNETIC REFRIGERATION SYSTEM WITH SEPARATED INLET AND OUTLET FLOW
EP3175186	2014	2017	ASTRONAUTICS CORP OF AMERICA	MAGNETIC REFRIGERATION SYSTEM WITH SEPARATED INLET AND OUTLET FLOW
EP3194863	2014	2017	ASTRONAUTICS CORP OF AMERICA	MAGNETIC REFRIGERATION SYSTEM WITH UNEQUAL BLOWS
9927155	2014	2018	ASTRONAUTICS CORP OF AMERICA	MAGNETIC REFRIGERATION SYSTEM WITH UNEQUAL BLOWS
9939170	2015	2018	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	METHODS AND COMPOSITIONS FOR RAPID THERMAL CYCLING
10119059	2012	2018	UNIVERSITY OF MARYLAND	THERMOELASTIC COOLING
10156369	2017	2018	ALLIANCE FOR SUSTAINABLE ENERGY LLC	SPLIT HEATING AND COOLING SYSTEMS
EP3295069	2016	2018	ALLIANCE FOR SUSTAINABLE ENERGY LLC	SPLIT HEATING AND COOLING SYSTEMS

Appendix AP-A. BTO-funded Appliance Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Original Assignees	Title
4107935	1977	1978	US DEPT OF ENERGY	HIGH TEMPERATURE REFRIGERATOR
4332135	1981	1982	US DEPT OF ENERGY	ACTIVE MAGNETIC REGENERATOR
4353218	1980	1982	US DEPT OF ENERGY	HEAT PUMP/REFRIGERATOR USING LIQUID WORKING FLUID
4398398	1981	1983	UNASSIGNED	ACOUSTICAL HEAT PUMPING ENGINE
4408463	1982	1983	UNASSIGNED	WHEEL-TYPE MAGNETIC REFRIGERATOR
4445340	1983	1984	US DEPT OF ENERGY	DILUTION CYCLE CONTROL FOR AN ABSORPTION REFRIGERATION SYSTEM
4458499	1982	1984	US DEPT OF ENERGY	ABSORPTION HEAT PUMP SYSTEM
4458500	1982	1984	US DEPT OF ENERGY	ABSORPTION HEAT PUMP SYSTEM
4459811	1983	1984	US DEPT OF ENERGY	MAGNETIC REFRIGERATION APPARATUS AND METHOD
4484456	1983	1984	US DEPT OF ENERGY	TRIPLE LOOP HEAT EXCHANGER FOR AN ABSORPTION REFRIGERATION SYSTEM
4485638	1983	1984	US DEPT OF ENERGY	HEAT EXCHANGER BYPASS SYSTEM FOR AN ABSORPTION REFRIGERATION SYSTEM
4542629	1984	1985	US DEPT OF ENERGY	VARIABLE EFFECT DESORBER-RESORBER ABSORPTION CYCLE
4546620	1984	1985	US DEPT OF ENERGY	ABSORPTION MACHINE WITH DESORBER-RESORBER
4674297	1984	1987	UNASSIGNED	CHEMICALLY ASSISTED MECHANICAL REFRIGERATION PROCESS
4683154	1985	1987	US DEPT OF ENERGY	LASER SEALED VACUUM INSULATION WINDOW
4707996	1986	1987	UNASSIGNED	CHEMICALLY ASSISTED MECHANICAL REFRIGERATION PROCESS
4996403	1990	1991	US DEPT OF ENERGY	ACOUSTIC EMISSION FEEDBACK CONTROL FOR CONTROL OF BOILING IN A MICROWAVE OVEN
5032439	1989	1991	MASSACHUSETTS INSTITUTE OF TECHNOLOGY	THERMAL INSULATIONS USING VACUUM PANELS
EP0447134	1991	1991	SONIC COMPRESSOR SYSTEMS INC	STANDING WAVE COMPRESSOR
WO1991002856	1990	1991	MASSACHUSETTS	THERMAL INSULATIONS

			INSTITUTE OF TECHNOLOGY	USING VACUUM PANELS
5090879	1990	1992	UNASSIGNED	RECIRCULATING ROTARY GAS COMPRESSOR
5148573	1991	1992	UNASSIGNED	APPARATUS FOR ATTACHING A CLEANING TOOL TO A ROBOTIC MANIPULATOR
5174130	1990	1992	SONIC COMPRESSOR SYSTEMS INC	REFRIGERATION SYSTEM HAVING STANDING WAVE COMPRESSOR
5205136	1992	1993	MARTIN MARIETTA ENERGY SYSTEMS INC	TRIPLE-EFFECT ABSORPTION REFRIGERATION SYSTEM WITH DOUBLE-CONDENSER COUPLING
5270092	1991	1993	UNIVERSITY OF CALIFORNIA	GAS FILLED PANEL INSULATION
WO1993002853	1992	1993	UNIVERSITY OF CALIFORNIA	GAS FILLED PANEL INSULATION
WO1993018355	1992	1993	MARTIN MARIETTA ENERGY SYSTEMS INC	TRIPLE-EFFECT ABSORPTION REFRIGERATION SYSTEM WITH DOUBLE-CONDENSER COUPLING
5321222	1991	1994	MARTIN MARIETTA ENERGY SYSTEMS INC	VARIABLE FREQUENCY MICROWAVE FURNACE SYSTEM
5357756	1993	1994	MARTIN MARIETTA ENERGY SYSTEMS INC	BIPOLAR PULSE FIELD FOR MAGNETIC REFRIGERATION
5376449	1993	1994	MARTIN MARIETTA ENERGY SYSTEMS INC	SILICA POWDERS FOR POWDER EVACUATED THERMAL INSULATING PANEL AND METHOD
EP0621825	1992	1994	UNIVERSITY OF CALIFORNIA	GAS FILLED PANEL INSULATION
EP0629279	1992	1994	MARTIN MARIETTA ENERGY SYSTEMS INC	TRIPLE-EFFECT ABSORPTION REFRIGERATION SYSTEM WITH DOUBLE-CONDENSER COUPLING.
5395604	1994	1995	MARTIN MARIETTA ENERGY SYSTEMS INC	SILICA POWDERS FOR POWDER EVACUATED THERMAL INSULATING PANEL AND METHOD
5467614	1994	1995	MARTIN MARIETTA ENERGY SYSTEMS INC	DUAL-CIRCUIT, MULTIPLE-EFFECT REFRIGERATION SYSTEM AND METHOD
5480696	1994	1996	US DEPT OF ENERGY	SILICA POWDERS FOR POWDER EVACUATED THERMAL INSULATING PANEL AND METHOD

5521360	1994	1996	MARTIN MARIETTA ENERGY SYSTEMS INC	APPARATUS AND METHOD FOR MICROWAVE PROCESSING OF MATERIALS
5622055	1995	1997	MARTIN MARIETTA ENERGY SYSTEMS INC	LIQUID OVER-FEEDING REFRIGERATION SYSTEM AND METHOD WITH INTEGRATED ACCUMULATOR-EXPANDER-HEAT EXCHANGER
5636520	1995	1997	SPAUSCHUS ASSOCIATES INC	METHOD OF REMOVING AN IMMISCIBLE LUBRICANT FROM AN REFRIGERATION SYSTEM
5689966	1996	1997	BATTELLE MEMORIAL INSTITUTE	METHOD AND APPARATUS FOR DESUPERHEATING REFRIGERANT
5750882	1997	1998	LOCKHEED MARTIN ENERGY RESEARCH CORP	GAS PERMEABILITY MEASUREMENTS FOR FILM ENVELOPE MATERIALS
5813454	1996	1998	VARITEC THERMAL LLC	VARIABLY INSULATING PORTABLE HEATER/COOLER
5887441	1997	1999	SPAUSCHUS ASSOCIATES INC	METHOD OF REMOVING AN IMMISCIBLE LUBRICANT FROM A REFRIGERATION SYSTEM AND APPARATUS FOR SAME
WO2000046557	2000	2000	MIDWEST RESEARCH INSTITUTE	REFRIGERATION SYSTEM WITH LIQUID INJECTION DESUPERHEATING
6185944	1999	2001	MIDWEST RESEARCH INSTITUTE	REFRIGERATION SYSTEM WITH A COMPRESSOR-PUMP UNIT AND A LIQUID-INJECTION DESUPERHEATING LINE
6222170	1999	2001	UT-BATTELLE LLC	APPARATUS AND METHOD FOR MICROWAVE PROCESSING OF MATERIALS USING FIELD-PERTURBING TOOL
6250090	1999	2001	LOCKHEED MARTIN ENERGY RESEARCH CORP	APPARATUS AND METHOD FOR EVAPORATOR DEFROSTING
EP1157244	2000	2001	MIDWEST RESEARCH INSTITUTE	REFRIGERATION SYSTEM WITH LIQUID INJECTION DESUPERHEATING
WO2001020235	2000	2001	UT-BATTELLE, LLC	APPARATUS AND METHOD FOR EVAPORATOR DEFROSTING
6467282	2001	2002	UNASSIGNED	FROST SENSOR FOR USE IN DEFROST CONTROLS FOR REFRIGERATION
WO2002065028	2002	2002	MIDWEST RESEARCH INSTITUTE	COMBINED REFRIGERATION SYSTEM WITH A LIQUID PRE-COOLING HEAT EXCHANGER

6584784	2001	2003	MIDWEST RESEARCH INSTITUTE	COMBINED REFRIGERATION SYSTEM WITH A LIQUID PRE-COOLING HEAT EXCHANGER
6637211	2002	2003	UNIVERSITY OF CALIFORNIA	CIRCULATING HEAT EXCHANGERS FOR OSCILLATING WAVE ENGINES AND REFRIGERATORS
6679083	2002	2004	UNASSIGNED	OPPOSED SLANT TUBE DIABATIC SORBER
WO2004015336	2003	2004	UNIVERSITY OF CALIFORNIA	CIRCULATING HEAT EXCHANGERS FOR OSCILLATING WAVE ENGINES AND REFRIGERATORS
WO2004113810	2004	2004	THE PROCTER & GAMBLE CO	PROCESS FOR INCREASING LIQUID EXTRACTION FROM FABRICS
WO2005074608	2005	2005	ASTRONAUTICS CORP OF AMERICA	PERMANENT MAGNET ASSEMBLY
7076959	2005	2006	BROOKHAVEN SCIENCE ASSOCIATES LLC	ENHANCED MAGNETOCALORIC EFFECT MATERIAL
7148777	2005	2006	ASTRONAUTICS CORP OF AMERICA	PERMANENT MAGNET ASSEMBLY
EP1634025	2004	2006	THE PROCTER & GAMBLE CO	PROCESS FOR INCREASING LIQUID EXTRACTION FROM FABRICS
EP1711953	2005	2006	ASTRONAUTICS CORP OF AMERICA	PERMANENT MAGNET ASSEMBLY
7559212	2006	2009	UNASSIGNED	REFRIGERANT PRESSURIZATION SYSTEM WITH A TWO-PHASE CONDENSING EJECTOR
WO2010118304	2010	2010	COLORADO STATE UNIV, UT-BATTELLE LLC	COOK STOVE ASSEMBLY
7954190	2004	2011	THE PROCTER & GAMBLE CO	PROCESS FOR INCREASING LIQUID EXTRACTION FROM FABRICS
WO2012060984	2011	2012	BATTELLE MEMORIAL INSTITUTE	OPEN-LOOP HEAT-RECOVERY DRYER
8572862	2010	2013	BATTELLE MEMORIAL INSTITUTE	OPEN-LOOP HEAT-RECOVERY DRYER
8596341	2008	2013	BATTELLE MEMORIAL INSTITUTE	ENHANCED TWO PHASE FLOW IN HEAT TRANSFER SYSTEMS
EP2631568	2013	2013	WHIRLPOOL CORP	REFRIGERATION ARRANGEMENT AND METHODS FOR REDUCING CHARGE MIGRATION LOSSES
EP2631572	2013	2013	WHIRLPOOL CORP	DUAL CAPILLARY TUBE /

				HEAT EXCHANGER IN COMBINATION WITH CYCLE PRIMING FOR REDUCING CHARGE MITIGATION
EP2631578	2013	2013	WHIRLPOOL CORP	REFRIGERATOR WITH VARIABLE CAPACITY COMPRESSOR AND CYCLE PRIMING ACTION THROUGH CAPACITY CONTROL AND ASSOCIATED METHODS
EP2667122	2013	2013	WHIRLPOOL CORP	SYNCHRONOUS TEMPERATURE RATE CONTROL AND APPARATUS FOR REFRIGERATION WITH REDUCED ENERGY CONSUMPTION
EP2667123	2013	2013	WHIRLPOOL CORP	SYNCHRONOUS TEMPERATURE RATE CONTROL FOR REFRIGERATION WITH REDUCED ENERGY CONSUMPTION
EP2667124	2013	2013	WHIRLPOOL CORP	SYNCHRONOUS COMPARTMENT TEMPERATURE CONTROL AND APPARATUS FOR REFRIGERATION WITH REDUCED ENERGY CONSUMPTION
8864251	2012	2014	WHIRLPOOL CORP	HYDROPHILIC STRUCTURES FOR CONDENSATION MANAGEMENT IN REFRIGERATOR APPLIANCES
8899222	2010	2014	COLORADO STATE UNIV, UT-BATTELLE LLC	COOK STOVE ASSEMBLY
EP2679936	2013	2014	WHIRLPOOL CORP	FAULT DETECTION AND DIAGNOSIS FOR REFRIGERATOR FROM COMPRESSOR SENSOR
EP2693142	2013	2014	WHIRLPOOL CORP	HYDROPHILIC STRUCTURES FOR CONDENSATION MANAGEMENT IN REFRIGERATOR APPLIANCES
8926032	2012	2015	WHIRLPOOL CORP	HYDROPHILIC STRUCTURE FOR CONDENSATION MANAGEMENT ON THE MOVABLE MULLION OF A REFRIGERATOR
9140477	2012	2015	WHIRLPOOL CORP	SYNCHRONOUS COMPARTMENT TEMPERATURE CONTROL AND APPARATUS FOR REFRIGERATION WITH

				REDUCED ENERGY CONSUMPTION
9140478	2012	2015	WHIRLPOOL CORP	SYNCHRONOUS TEMPERATURE RATE CONTROL FOR REFRIGERATION WITH REDUCED ENERGY CONSUMPTION
9140479	2012	2015	WHIRLPOOL CORP	SYNCHRONOUS TEMPERATURE RATE CONTROL AND APPARATUS FOR REFRIGERATION WITH REDUCED ENERGY CONSUMPTION
9250007	2014	2016	WHIRLPOOL CORP	HYDROPHILIC STRUCTURES FOR CONDENSATION MANAGEMENT IN APPLIANCES
9285161	2012	2016	WHIRLPOOL CORP	REFRIGERATOR WITH VARIABLE CAPACITY COMPRESSOR AND CYCLE PRIMING ACTION THROUGH CAPACITY CONTROL AND ASSOCIATED METHODS
9513043	2012	2016	WHIRLPOOL CORP	FAULT DETECTION AND DIAGNOSIS FOR REFRIGERATOR FROM COMPRESSOR SENSOR
9618246	2012	2017	WHIRLPOOL CORP	REFRIGERATION ARRANGEMENT AND METHODS FOR REDUCING CHARGE MIGRATION
9696077	2012	2017	WHIRLPOOL CORP	DUAL CAPILLARY TUBE / HEAT EXCHANGER IN COMBINATION WITH CYCLE PRIMING FOR REDUCING CHARGE MIGRATION
9791221	2012	2017	WHIRLPOOL CORP	CONDENSER ASSEMBLY SYSTEM FOR AN APPLIANCE
9810472	2015	2017	WHIRLPOOL CORP	SYNCHRONOUS TEMPERATURE RATE CONTROL FOR REFRIGERATION WITH REDUCED ENERGY CONSUMPTION
9949611	2017	2018	UT-BATTELLE LLC	CONFIGURATION OF DISHWASHER TO IMPROVE ENERGY EFFICIENCY OF WATER HEATING
10208993	2016	2019	WHIRLPOOL CORP	FAULT DETECTION AND DIAGNOSIS FOR REFRIGERATOR FROM COMPRESSOR SENSOR

Appendix AP-B. Other DOE-funded Appliance Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Original Assignees	Title
4158295	1978	1979	CARRIER CORP	SPRAY GENERATORS FOR ABSORPTION REFRIGERATION SYSTEMS
4441902	1982	1984	KAMAN SCIENCES CORP	HEAT RECLAIMING METHOD AND APPARATUS
4688399	1986	1987	CARRIER CORP	HEAT PIPE ARRAY HEAT EXCHANGER
5743095	1996	1998	IOWA STATE UNIVERSITY	ACTIVE MAGNETIC REFRIGERANTS BASED ON GD-SI-GE MATERIAL AND REFRIGERATION APPARATUS AND PROCESS
6589366	2001	2003	IOWA STATE UNIVERSITY	METHOD OF MAKING ACTIVE MAGNETIC REFRIGERANT, COLOSSAL MAGNETOSTRICTION AND GIANT MAGNETORESISTIVE MATERIALS BASED ON GD-SI-GE ALLOYS
7114340	2003	2006	IOWA STATE UNIVERSITY	METHOD OF MAKING ACTIVE MAGNETIC REFRIGERANT MATERIALS BASED ON GD-SI-GE ALLOYS
7260956	2005	2007	UNIVERSITY OF WYOMING	SYSTEM FOR MAINTAINING MATERIALS AT FREEZER TEMPERATURES FOR SHIPPING
8522562	2011	2013	UT-BATTELLE LLC	APPARATUS AND METHOD FOR MAGNETICALLY PROCESSING A SPECIMEN

Appendix WH-A. BTO-funded Water Heating Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Original Assignees	Title
4173872	1978	1979	ENERGY UTILIZATION SYSTEMS INC	WATER HEATER APPARATUS
4248295	1980	1981	THERMACORE INC	FREEZABLE HEAT PIPE
4336837	1981	1982	US DEPT OF ENERGY	ENTIRELY PASSIVE HEAT PIPE APPARATUS CAPABLE OF OPERATING AGAINST GRAVITY
4361135	1981	1982	US DEPT OF ENERGY	COOPERATIVE HEAT TRANSFER AND GROUND COUPLED STORAGE SYSTEM
4390008	1980	1983	US DEPT OF ENERGY	HOT WATER TANK FOR USE WITH A COMBINATION OF SOLAR ENERGY AND HEAT-PUMP DESUPERHEATING
4523629	1982	1985	US DEPT OF ENERGY	METHOD AND APPARATUS FOR OPERATING AN IMPROVED THERMOCLINE STORAGE UNIT
5143149	1991	1992	UNASSIGNED	WASTEWATER HEAT RECOVERY APPARATUS
5431148	1994	1995	US DEPT OF ENERGY	IMMERSIBLE SOLAR HEATER FOR FLUIDS
5687706	1995	1997	UNIVERSITY OF FLORIDA	PHASE CHANGE MATERIAL STORAGE HEATER
5906109	1998	1999	ARTHUR D LITTLE INC	HEAT PUMP WATER HEATER AND STORAGE TANK ASSEMBLY
5946927	1998	1999	ARTHUR D LITTLE INC	HEAT PUMP WATER HEATER AND STORAGE TANK ASSEMBLY
WO1999053249	1999	1999	US DEPT OF ENERGY	HEAT PUMP WATER HEATER AND STORAGE TANK ASSEMBLY
6199395	1999	2001	ARTHUR D LITTLE INC	CONDENSATE HANDLING ASSEMBLY AND METHOD
6233958	1999	2001	LOCKHEED MARTIN ENERGY RESEARCH CORP	HEAT PUMP WATER HEATER AND METHOD OF MAKING THE SAME
6257002	2000	2001	ARTHUR D LITTLE INC	CONDENSATE HANDLING ASSEMBLY AND METHOD
WO2001016536	2000	2001	ARTHUR D LITTLE INC	A CONDENSATE HANDLING ASSEMBLY AND METHOD
WO2001020232	2000	2001	UT-BATTELLE, LLC.	IMPROVED HEAT PUMP WATER HEATER AND METHOD OF MAKING THE SAME
WO2001029285	2000	2001	ADVANCED MECHANICAL TECHNOLOGY INC	CORROSION PROTECTION OF STEEL IN AMMONIA/WATER HEAT PUMPS
6632294	2001	2003	ADVANCED MECHANICAL	CORROSION PROTECTION OF STEEL IN AMMONIA/WATER

			TECHNOLOGY INC	HEAT PUMPS
6663380	2001	2003	GAS TECHNOLOGY INSTITUTE	METHOD AND APPARATUS FOR ADVANCED STAGED COMBUSTION UTILIZING FORCED INTERNAL RECIRCULATION
6675746	2001	2004	ADVANCED MECHANICAL TECHNOLOGY INC	HEAT EXCHANGER WITH INTERNAL PIN ELEMENTS
6814070	2003	2004	DAVIS ENERGY GROUP INC	MOLDED POLYMER SOLAR WATER HEATER
WO2005003544	2004	2005	PHILIP MORRIS USA INC	IMPINGEMENT HEAT EXCHANGER FOR A STIRLING CYCLE MACHINE
7028490	2004	2006	UT-BATTELLE LLC	WATER-HEATING DEHUMIDIFIER
7114334	2004	2006	TIAX LLC	IMPINGEMENT HEAT EXCHANGER FOR STIRLING CYCLE MACHINES
EP1644630	2004	2006	PHILIP MORRIS USA INC	IMPINGEMENT HEAT EXCHANGER FOR A STIRLING CYCLE MACHINE
8590802	2009	2013	BATTELLE MEMORIAL INSTITUTE	WATER HEATER CONTROL MODULE
WO2013096269	2012	2013	NORDYNE INC	REFRIGERANT CHARGE MANAGEMENT IN A HEAT PUMP WATER HEATER
8756943	2012	2014	NORDYNE LLC	REFRIGERANT CHARGE MANAGEMENT IN A HEAT PUMP WATER HEATER
EP2823242	2012	2015	NORDYNE LLC	REFRIGERANT CHARGE MANAGEMENT IN A HEAT PUMP WATER HEATER
WO2015116362	2015	2015	UNIVERSITY OF FLORIDA, UT-BATTELLE LLC	OPEN ABSORPTION CYCLE FOR DEHUMIDIFICATION, WATER HEATING, AND EVAPORATIVE COOLING
WO2015187667	2015	2015	UNIVERSITY OF FLORIDA	ARCHITECTURE FOR ABSORPTION BASED HEATERS
9383126	2014	2016	NORTEK GLOBAL HVAC LLC	REFRIGERANT CHARGE MANAGEMENT IN A HEAT PUMP WATER HEATER
9951976	2015	2018	UNIVERSITY OF FLORIDA	ARCHITECTURE FOR ABSORPTION BASED HEATERS
10151498	2016	2018	UNIVERSITY OF FLORIDA, UT-BATTELLE LLC	OPEN ABSORPTION CYCLE FOR COMBINED DEHUMIDIFICATION, WATER HEATING, AND EVAPORATIVE COOLING

Appendix WH-B. Other DOE-funded Water Heating Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Original Assignees	Title
4411307	1981	1983	ATLANTIC RICHFIELD CO	WOUND TUBE HEAT EXCHANGER
4478275	1983	1984	THERMACORE INC	ABRASION RESISTANT HEAT PIPE
6722358	2001	2004	FAFCO INC	INTEGRAL COLLECTOR STORAGE SYSTEM WITH HEAT EXCHANGE APPARATUS
6971336	2005	2005	GAS TECHNOLOGY INSTITUTE	SUPER LOW NOx, HIGH EFFICIENCY, COMPACT FIRETUBE BOILER
7066396	2004	2006	GAS TECHNOLOGY INSTITUTE	METHOD AND APPARATUS FOR ENHANCED HEAT RECOVERY FROM STEAM GENERATORS AND WATER HEATERS
WO2006135392	2005	2006	NEUCO INC	METHOD AND SYSTEM FOR SCR OPTIMIZATION
7500437	2004	2009	NEUCO INC	METHOD AND SYSTEM FOR SCR OPTIMIZATION
WO2009054945	2008	2009	LOS ALAMOS NATIONAL SECURITY LLC	IN-LINE STIRLING ENGINE SYSTEM
WO2009102510	2009	2009	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	SOLAR THERMAL POWER SYSTEM
7735323	2008	2010	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	SOLAR THERMAL POWER SYSTEM
7908856	2007	2011	LOS ALAMOS NATIONAL SECURITY LLC	IN-LINE STIRLING ENERGY SYSTEM
WO2013048617	2012	2013	BATTELLE MEMORIAL INSTITUTE	THERMAL ENERGY STORAGE DEVICES, SYSTEMS, AND THERMAL ENERGY STORAGE DEVICE MONITORING METHODS
9441889	2011	2016	BATTELLE MEMORIAL INSTITUTE	THERMAL ENERGY STORAGE DEVICES, SYSTEMS, AND THERMAL ENERGY STORAGE DEVICE MONITORING METHODS
9863662	2011	2018	WILLIAM MARSH RICE UNIVERSITY	GENERATING A HEATED FLUID USING AN ELECTROMAGNETIC RADIATION-ABSORBING COMPLEX

Report prepared by 1790 Analytics LLC DOE/EE Publication Number: 2374