The Influence of Geothermal Patents Funded by the U.S. Department of Energy's Geothermal Energy 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 geothermal energy research funded by the U.S. Department of Energy (DOE)'s Geothermal Technologies Office (GTO) and its precursor programs, as well as geothermal energy research funded by other offices in DOE. The tracing 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 GTO-funded geothermal energy research has formed a foundation for innovations patented by leading geothermal energy organizations. Meanwhile, the primary purpose of the forward tracing is to examine the broader influence of GTO-funded geothermal energy research upon subsequent technological developments, both within and outside geothermal technology. In addition to these GTO-based analyses, we also extend many elements of the analysis to other DOE-funded geothermal energy patents, in order to gain insights into their influence.

The main finding of this report is:

- Geothermal energy research funded by GTO, and by DOE in general, has had a significant influence on subsequent developments, both within and beyond geothermal technology. This influence can be seen upon innovations associated with the leading geothermal energy companies. It can also be traced in other technologies, notably oil and gas exploration, energy storage, materials handling and wastewater treatment.

More detailed findings from this report include:

- In geothermal energy technology, in the period 1976-2018, we identified a total of 3,408 patents (1,219 U.S. patents, 898 EPO patents and 1,291 WIPO patents). We grouped these patents into 2,646 patent families, where each family contains all patents resulting from the same initial application (named the priority application).

- 118 geothermal energy patents are confirmed to be associated with GTO funding (95 U.S. patents, 9 EPO patents, and 14 WIPO patents). We grouped these GTO-funded geothermal energy patents into 75 patent families.

- In addition, we identified a further 128 geothermal energy patents (87 U.S. patents, 13 EPO patents and 28 WIPO patents) that are associated with DOE funding. These "Other DOE-funded" patents are grouped into 61 patent families.

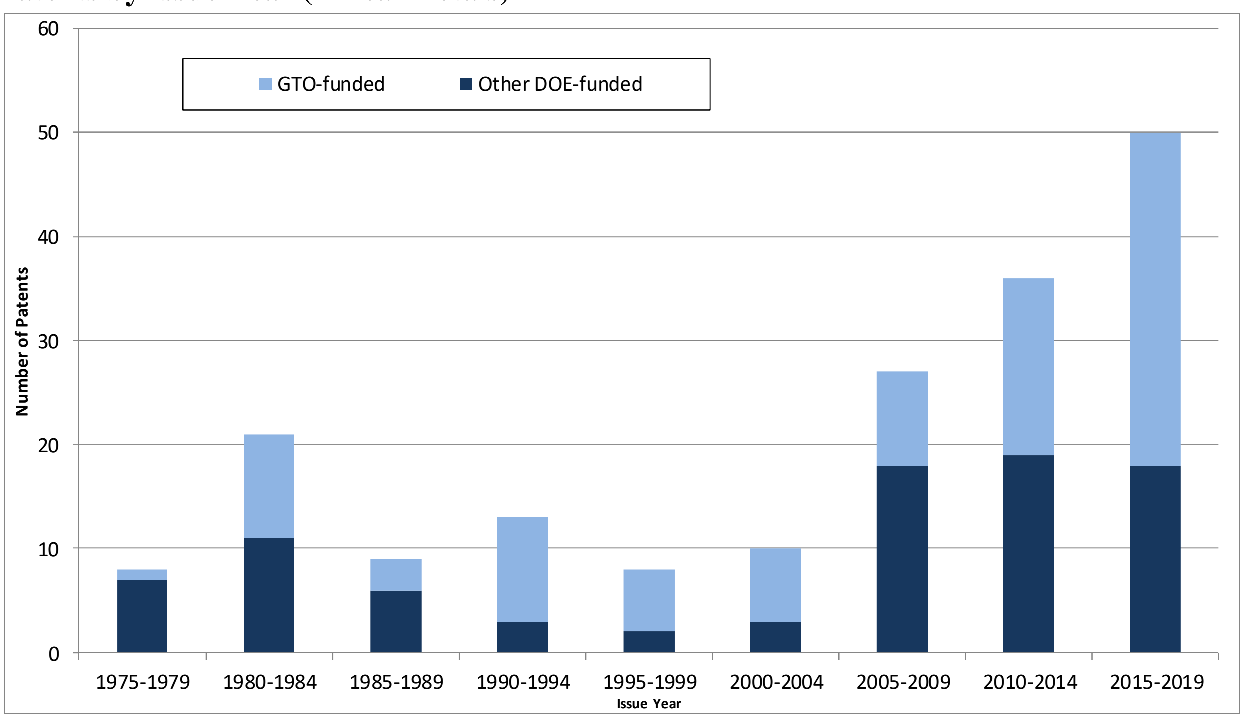
- Out of these 61 Other DOE-funded patent families, 29 are definitely not GTO-funded. These patent families were either funded by a different DOE office, or were marked as being not GTO-funded by inventors or GTO technology managers, but without specifying funding from another DOE source.

- The remaining 32 Other DOE-funded geothermal energy patent families could not be linked definitively to a specific DOE funding source, and may in fact have been GTO-funded. Hence, up to 52% (32 out of 61) of the Other DOE-funded geothermal energy patent families in this analysis may in fact be GTO-funded. As such, the results presented in this report may understate the influence of GTO-funded geothermal energy research, relative to the influence of geothermal energy research funded by DOE in general.

- The total number of DOE-funded geothermal energy patents (GTO-funded plus Other DOE-funded) is 246, corresponding to 136 patent families. This represents 5.1% of the total number of geothermal energy patent families in the period 1976-2018.

- Figure E-1 shows the number of GTO-funded and Other DOE-funded geothermal energy U.S. patents by issue year. This figure shows that there was an initial period of active DOE-funded patenting in 1980-1984, followed by a relatively quiet period during the next time periods. The number of U.S. patents then increased sharply in 2005-2009, and continued to increase, peaking at 50 U.S. patents granted in 2015-2019 (32 of which are GTO-funded), even though data for this most recent time period are incomplete (see note below Figure E-1).

Figure E-1 - Number of GTO/Other DOE-funded Geothermal Energy 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.

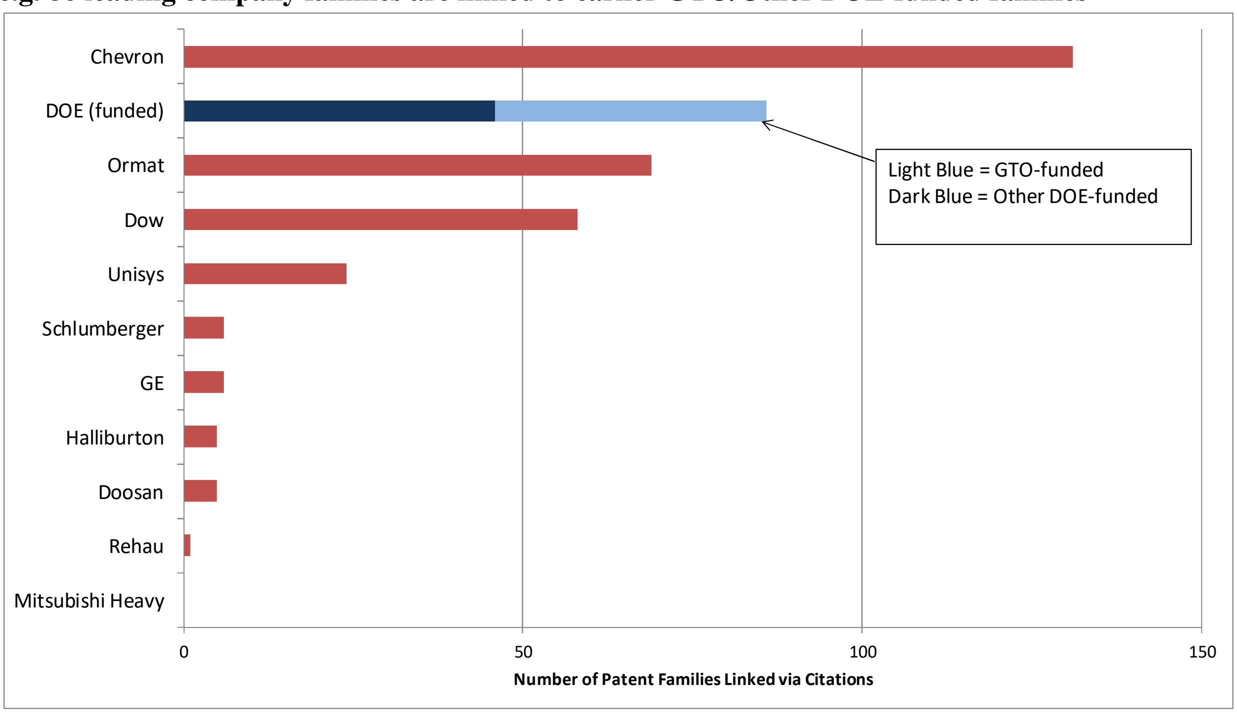
- The ten companies with the largest geothermal energy patent portfolios are: Chevron (96 patent families); General Electric (57); Ormat (53); Dow Chemical (27); Unisys (22);

Halliburton (21); Rehau (20); Schlumberger (16); Doosan Holdings (16); and Mitsubishi Heavy Industries (15). The portfolio of 136 DOE-funded geothermal energy patent families (75 GTO-funded and 61 Other DOE-funded) is thus larger than the portfolios of each of the leading companies.

- Taking the period 1976-2018 as a whole, GTO-funded and Other DOE-funded geothermal patents have focused primarily on physical aspects of downhole technology (surveying, drilling etc.). Meanwhile, the leading companies, and geothermal patents in general, have a greater concentration on generating power from geothermal brines. This difference in focus suggests that GTO-funded and Other DOE-funded geothermal research has helped to fill a gap not addressed extensively by the leading companies.

- In total, 86 leading company geothermal energy patent families (i.e. 25% of these 343 families) are linked via citations to earlier DOE-funded geothermal energy patents, out of which 40 are linked to GTO-funded geothermal energy patents. This finding puts DOE-funded patents in second place in Figure E-2, behind Chevron (with 131 leading company patent families linked to its earlier patents). As such, it suggests that the leading companies have built extensively on the portfolios of GTO-funded and Other DOE-funded geothermal patents.

Figure E-2 - Number of Leading Company Geothermal Patent Families Linked via Citations to Earlier Geothermal Patents from each Leading Company
e.g. 86 leading company families are linked to earlier GTO/Other DOE-funded families

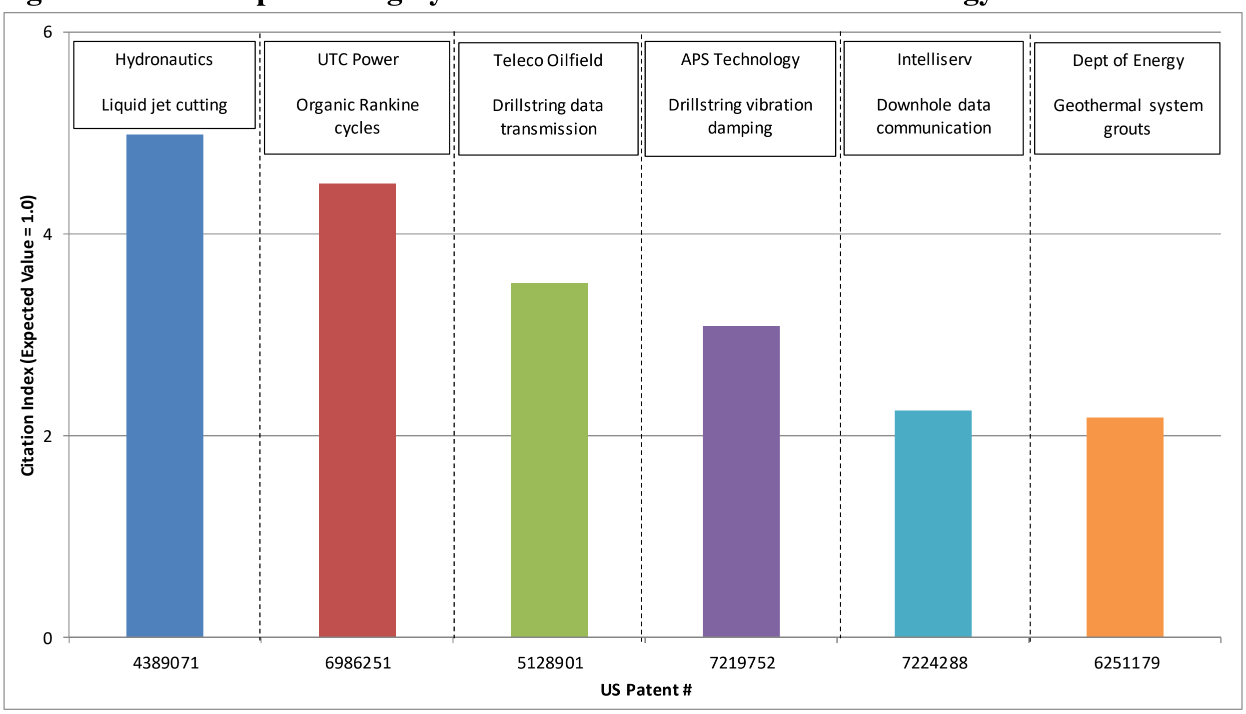


- Over half of Halliburton's geothermal energy patent families are linked via citations to earlier GTO-funded geothermal patents. Chevron, General Electric and Ormat also have extensive citation links to GTO-funded patents. This suggests that GTO-funded research has had a particularly strong influence on innovations from these companies.

- GTO-funded geothermal energy patents have an average Citation Index value of 1.30 (the Citation Index is a normalized citation metric with an expected value of 1.0; a value of 1.30 shows that, based on their age and technology, GTO-funded geothermal energy patents have been cited as prior art 30% more frequently than expected by subsequent patents). The Citation Index for Other DOE-funded geothermal energy patents is even higher at 2.66, showing that these patents have been cited more than two-and-a-half times as frequently as expected. The influence of GTO-funded and Other DOE-funded geothermal energy patents has been primarily within geothermal and oilfield technologies, but can also be traced in other technologies such as energy storage, material handling and wastewater treatment.

- There are a number of individual high-impact GTO-funded geothermal energy patents, examples of which are shown in Figure E-3. They include Hydronautics patents for high velocity liquid jets that can be used in drilling applications; UTC Power patents describing organic Rankine cycles; Teleco Oilfield Services and Intelliserv patents outlining downhole data transmission; APS Technology patents for reducing drill string vibration; and DOE patents describing grouts for geothermal heat pumps.

Figure E-3 – Examples of Highly-Cited GTO-funded Geothermal Energy Patents



1.0 Introduction

This report focuses on geothermal energy technology. Its objective is to trace the influence of geothermal energy research funded by the Department of Energy (DOE) Geothermal Energy Technologies Office (GTO) – as well as geothermal energy research funded by DOE as a whole – upon subsequent developments both within and outside geothermal energy. The purpose of the report is to:

(i) Locate patents awarded for key GTO-funded (and other DOE-funded) innovations in geothermal energy; and

(ii) Determine the extent to which GTO-funded (and other DOE-funded) geothermal energy research has influenced subsequent technological developments both within and beyond geothermal energy.

The primary focus of the report is on the influence of GTO-funded geothermal energy patents. That said, we also extend many elements of the analysis to DOE-funded geothermal energy patents that could not be definitively linked to GTO funding. There are both evaluative and practical reasons for extending the analysis in this way. From an evaluation perspective, it is interesting to examine the influence of GTO itself upon the development of geothermal energy technology, while also tracing the influence of DOE more generally. Meanwhile, in practical terms, determining which patents were funded by GTO, versus other offices within DOE, is often very difficult.

In the U.S. patent system, applicants are required to acknowledge any government funding they have received related to the invention described in their patent application. Typically, this government support is reported at the level of the agency (e.g. Department of Energy, Department of Defense, etc.). Hence, the only way to determine which office within DOE funded a given patent is via other data resources (e.g. iEdison), or through direct input from offices, program managers and individual inventors. For older patents, such information is often unavailable, because records may be less comprehensive, and there is less access to the inventors and program managers involved.

Rather than discard patents confirmed as DOE-funded, but that could not be definitively categorized as GTO-funded, we instead included these patents in the analysis under a separate "Other DOE-funded" category. Some of these patents are confirmed as being linked to funding from other DOE offices, while for others the source of funding within DOE is unknown. Many of these "unknown" patents may in fact have been funded by GTO, although a definitive link could not be established. Hence, the results reported here may underestimate the influence of GTO-funded geothermal energy research, relative to the influence of geothermal energy research funded by the rest of DOE.

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 presents the results of our analysis. Results are presented at the organizational level for both GTO-funded and Other DOE-funded patents. These results show the distribution of GTO-funded (and Other DOE-funded) patents across geothermal energy technologies (as defined by Cooperative Patent Classifications). They also evaluate the extent of GTO's influence (and DOE's influence in general) on subsequent developments in geothermal energy and other technologies. Patent level results are then presented to highlight individual GTO-funded geothermal energy patents that have been particularly influential, as well as to reveal key patents from other organizations that build extensively on GTO-funded geothermal energy research.[1]

2.0 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 technologies developed by leading companies in the geothermal energy industry have used GTO-funded research as a foundation. Meanwhile, the primary purpose of the forward tracing is to examine how GTO-funded geothermal energy patents influenced subsequent technological developments more broadly, both within and outside geothermal technology. 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 upon the leading geothermal energy companies.[2]

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 linkages between DOE-funded geothermal energy research and subsequent innovations. Examining all of these linkage types at the level of an entire technology 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.

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[1] 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] The analyses described in this report were carried out separately for GTO-funded and Other DOE-funded geothermal energy patents. However, referring repeatedly to "GTO-funded/Other DOE-funded patents" or "GTO-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.

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 papers 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 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.[3]

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 geothermal energy research. Specifically, we identify cases where patents cite DOE-funded geothermal energy 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 geothermal energy patents. These represent second-generation links between innovations and

[3] 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.

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

Forward and Backward Tracing

As noted above, the purpose of this analysis is to trace the influence of DOE-funded geothermal energy research upon subsequent developments both within and beyond geothermal technology. 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 geothermal energy 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 geothermal energy organizations build on earlier GTO-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 geothermal energy patents resulting from research funded by DOE (i.e. GTO plus Other DOE). The influence of these patents on later generations of technology is then evaluated. This tracing is not restricted to subsequent geothermal energy patents, since the influence of a body of research may extend beyond its immediate technology. Hence, the forward tracing element of the project evaluates the influence of DOE-funded geothermal energy patents upon developments both inside and outside this technology.

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.[4] The backward tracing starts with patents assigned to the leading patenting organizations in geothermal technology. 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 geothermal energy patents owned by leading organizations in this technology, and traces back through two generations of patents to identify the technologies upon which they were built, including those funded by DOE. Meanwhile, the forward tracing starts with DOE-funded patents in geothermal technology. 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. Hence, the analysis starts with DOE-funded geothermal energy patents and traces forward for two generations of subsequent patents.

[4] As noted above, the forward and backward tracing were carried out separately for GTO-funded and Other DOE-funded geothermal energy 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 geothermal energy patents as a single portfolio.

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

1. **Direct Links**: where a patent cites a DOE-funded geothermal energy patent as prior art.
2. **Indirect Links**: where a patent cites an earlier patent, which in turn cites a DOE-funded geothermal energy patent. The DOE patent is linked indirectly to the subsequent 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. 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 prior art references 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.[5] In addition, in some systems – notably the U.S. – inventors may apply for a series of patents based on one 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 geothermal energy patents, and also for the patents owned by leading geothermal energy organizations. We also assembled families for all patents linked via citations to DOE-funded geothermal energy patents. To construct these 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

[5] 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.

result in U.S., EPO and WIPO patents, which are grouped in the same patent family because they share the same Japanese priority document.

Metrics Used in the Analysis

Table 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 1 – List of Metrics Used in the Analysis

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

3.0 Methodology

The previous section of the report outlines the objective of our analysis – that is, to determine the influence of GTO-funded (and Other DOE-funded) geothermal energy research on subsequent developments both within and outside geothermal technology. 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 geothermal energy patents owned by leading patenting organizations in this technology. Meanwhile, the forward tracing starts from the sets of geothermal energy patents funded by GTO and Other DOE. We therefore had to define various data sets – GTO-funded geothermal energy patents; Other DOE-funded geothermal energy patents; and geothermal energy patents assigned to the leading organizations in this technology.

Identifying GTO-funded and Other DOE-funded Geothermal Energy Patents

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

(i) Defining the universe of DOE-funded patents;
(ii) Determining which of these DOE-funded patents are relevant to geothermal energy;
(iii) Categorizing these DOE-funded geothermal energy patents according to whether or not they can be linked definitively to GTO 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 resulting 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 take all of their patents and define them as DOE-funded. A further complication is that DOE does not only fund research in its own labs and research centers, it also funds extramural research carried out by other organizations. If this research results in patented inventions, these patents may 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 file containing 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 Geothermal Energy Patents

Having defined the universe of DOE-funded patents, the next step was to determine which of these patents are relevant to geothermal technology. We designed a custom patent filter to identify geothermal energy patents, consisting of a combination of Cooperative Patent Classifications (CPCs) and keywords. Details of the patent filter are shown in Table 2. The form of the filter is (Filter A OR Filter B OR Filter C), so patents that qualify under any of the three filters in Table 2 were included in the initial patent set.[6]

Table 2 – Filters used to identify DOE-funded Geothermal Energy Patents

Filter A
Cooperative Patent Classification
Y02B 10/40 – Geothermal heat pumps
Y02E 10/10-18 – Geothermal energy
F03G 7/04 – Motors using natural thermal differences
F24T – Geothermal collectors and systems
Filter B
Cooperative Patent Classification
G01V - Geophysics
AND
Title/Abstract
(hydro(-)therm* OR hot(-)rock* OR hot(-)dry(-)rock* OR molten(-)rock* OR rankine*)
Filter C
Title/Abstract
Geo(-)thermal*

We manually checked this initial list of patents to determine which of them appear relevant to geothermal energy, and then sent the resulting patent list to GTO for review. Following this review, and based on feedback from GTO, the initial list of geothermal energy patents funded by DOE contained a total of 182 granted U.S. patents.

Defining GTO-funded vs. Other DOE-funded Geothermal Energy 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 182 DOE-funded geothermal energy patents in the initial list could be linked definitively to GTO 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 GTO technology managers to verify individual patents,
(iv) Asking GTO technology managers to send lab patents to lab POCs to get direct verification of these patents,

[6] Note that there are many overlaps between CPCs covering geothermal and oilfield technologies, such as in drilling techniques, underground surveying and downhole data transmission. In order to avoid the geothermal patent set being overwhelmed by the much larger oilfield patent set, we did not include CPCs directed to these technologies. Instead, patents in these CPCs are included if they make specific mention of a geothermal application (see Filter C).

(v) Contacting individual inventors listed on patents to ask them to confirm whether individual patents were funded by GTO, and
(vi) Locating references to patents in available office annual project progress reports or patent disclosure documents with accomplishments reported by PIs.

Final List of GTO-funded and Other DOE-funded Geothermal Energy Patents

Based on the process described above, we divided the initial list of 182 DOE-funded geothermal energy U.S. patents into two categories – GTO-funded and Other DOE-funded. 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. We then grouped the patents into families by matching priority documents (see earlier discussion of patent families). Table 3 contains a summary of the final number of GTO-funded and Other DOE-funded geothermal energy patents and patent families.

Table 3 – Number of GTO-funded and Other DOE-funded Geothermal Energy Patents and Patent Families

	# Patent Families	# U.S. Patents	# EPO Patents	# WIPO Patents
GTO-funded	75	95	9	14
Other DOE-funded	61	87	13	28
Total DOE-funded	136	182	22	42

Table 3 shows that we identified a total of 75 GTO-funded geothermal energy patent families, containing 95 U.S. patents, 9 EPO patents, and 14 WIPO patents (see Appendix A for patent list). We also identified 61 Other DOE-funded geothermal energy patent families, containing 87 U.S. patents, 13 EPO patents, and 28 WIPO patents (see Appendix B for patent list). These DOE-funded portfolios include patents back to the mid-1970s, the starting point for this analysis.

As noted throughout this report, the approach used to define patents as GTO-funded was very stringent. Hence, a number of the 61 Other DOE-funded patent families may in fact have been funded by GTO, but are not categorized as such because a definite link could not be established. To get a better sense of how many of these Other DOE-funded patents (and patent families) may in fact be GTO-funded, we divided them into two groups.

The first group contains DOE-funded patent families that were definitely not funded by GTO. These include families linked specifically to funding from an office other than GTO, or that the inventor or GTO technology manager said were not funded by GTO (but without specifying funding from a different office). There are 29 such patent families. The second group contains DOE-funded patent families where the funding source within DOE could not be established, and inventors and GTO technology managers could not state categorically whether or not they were funded by GTO. There are 32 such patent families. Hence, up to 52% (32 out of 61) of the Other DOE-funded patent families included in this analysis may in fact be GTO-funded. As a result, the findings in this analysis may understate the influence of GTO-funded geothermal energy patents, relative to the influence of the remainder of DOE patents.

Identifying Geothermal Energy Patents Assigned to Leading Organizations

The backward tracing element of our analysis is designed to evaluate the influence of GTO-funded (and Other DOE-funded) research on geothermal energy innovations produced by leading organizations in this technology. To identify such organizations, we first defined the universe of geothermal energy patents in the period 1976-2018 using the patent filter detailed earlier in Table 2. Based on this filter, we identified a total of 1,219 geothermal energy U.S. patents, 898 geothermal energy EPO patents, and 1,291 geothermal energy WIPO patents. We grouped these patents into 2,646 patent families by matching priority documents.

We then located the most prolific patenting organizations in this overall geothermal energy patent universe, based on number of patent families. The ten organizations with the largest number of geothermal energy patent families are shown in Table 4.[7] The number of patent families listed in this table includes all variant names under which these companies have patents, taking into account including all subsidiaries and acquisitions.

Table 4 – Top 10 Patenting Geothermal Energy Companies

Company	# Geothermal Patent Families
Chevron	96
General Electric	57
Ormat	53
Dow Chemical	27
Unisys	22
Halliburton	21
Rehau	20
Schlumberger	16
Doosan	16
Mitsubishi Heavy Industries	15

Constructing Citation Links

Through the processes described above, we constructed starting patent sets for both the backward forward tracing elements of the analysis. The patent set for the backward tracing consisted of patent families assigned to the leading patenting organizations in geothermal technology. The patent sets for the forward tracing consisted of GTO-funded (and, separately, Other DOE-funded) geothermal energy patent families. We then traced backward through two generations of citations from the leading organizations' geothermal energy patents, and forward through two generations of citations from the GTO/Other DOE-funded geothermal energy 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.

[7] All ten of these organizations are companies. For clarity, they are referred to in the results section as the leading geothermal energy companies, rather than organizations. Note that they are selected based on patent portfolio size, which does not necessarily reflect units sold, revenues etc. A fuller description would be the leading patenting geothermal energy companies, but this is a cumbersome term to use throughout the results section of the report.

4.0 Results

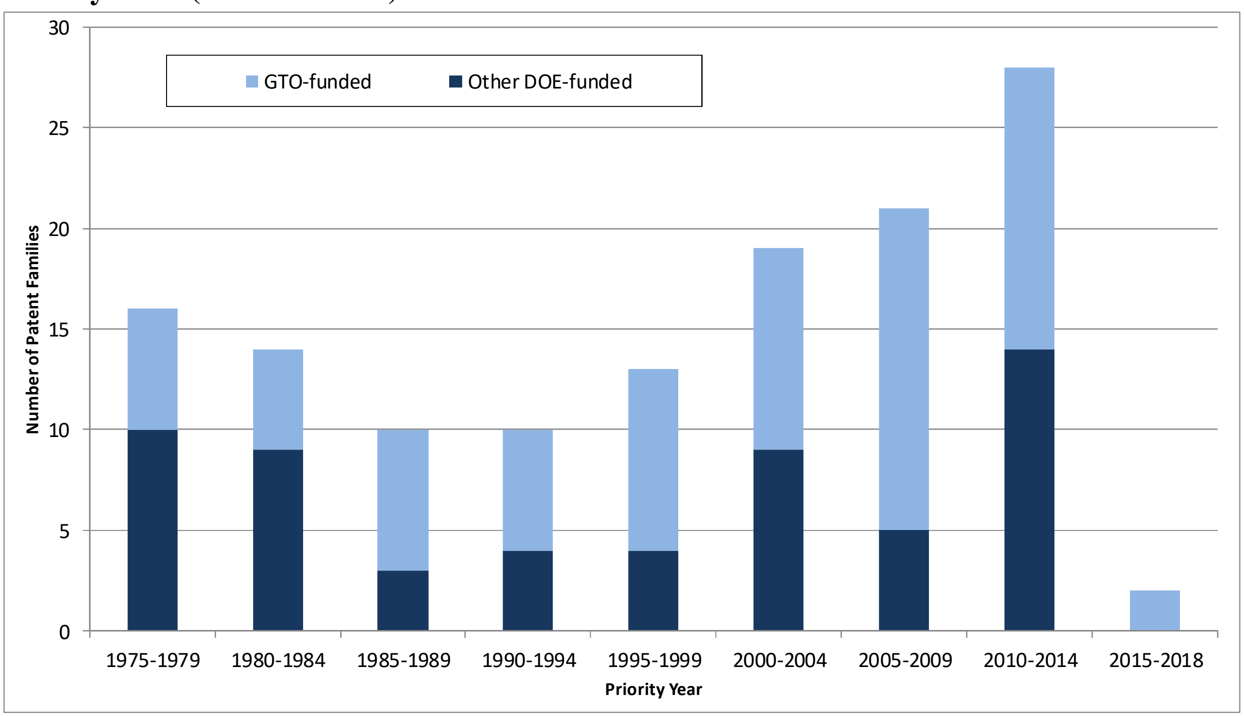
This section of the report outlines the results of our analysis tracing the influence of GTO-funded and Other DOE-funded geothermal energy research on subsequent developments both within and beyond geothermal technology. The results are divided into three main sections. In the first section, we examine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

Overall Trends in Geothermal Energy Patenting

Trends in Geothermal Energy Patenting over Time

Figure 1 shows the number of GTO-funded and Other DOE-funded geothermal energy patent families by priority year – i.e. the year of the first application in each patent family. GTO-funded patent families are shown in light blue and Other DOE-funded families in dark blue.

Figure 1 - Number of GTO/Other DOE-funded Geothermal Energy Patent Families by Priority Year (5-Year Totals)

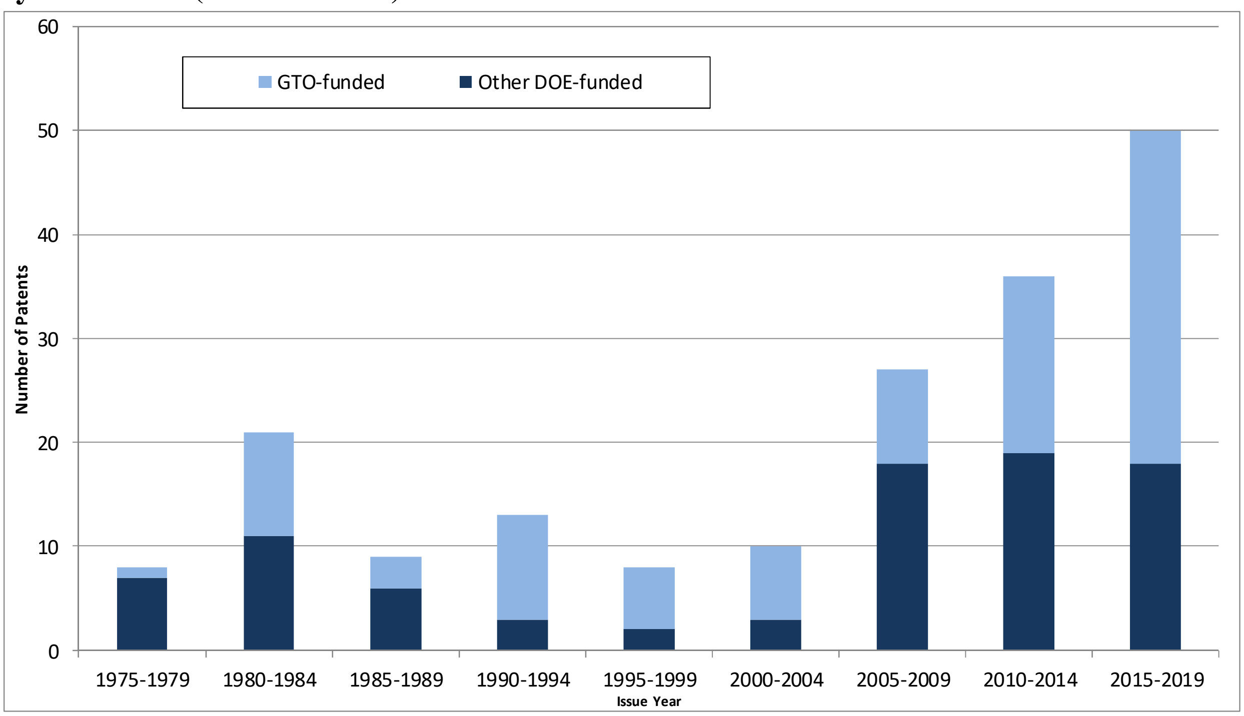


Note: The final time period in this figure is 2015-2018, and is shown for completeness, although data for this time period are incomplete. Our primary data collection covered only patents issued through 2018. Due to time lags associated with the patenting process, only a fraction of the patent families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

This figure reveals that DOE-funded geothermal patenting followed a U-shaped trend during the period covered by the analysis. There were sixteen DOE-funded patent families filed in 1975-1979 (six of them GTO-funded), followed by fourteen in 1980-1984 (five GTO-funded). In both 1985-1989 and 1990-1994, there were only ten DOE-funded families, most of which were GTO-funded. From 1995 onwards, the number of DOE-funded geothermal patent families increased, and continued grow in each time period, peaking at 28 families filed in 2010-2014 (half of them GTO-funded). The number of DOE-funded patent families fell sharply in 2015-2018, but data for this time period are incomplete (see note below Figure 1). Overall, there are 136 DOE-funded geothermal energy patent families, 75 of which are GTO-funded.

Figure 2 shows the number of geothermal energy granted U.S. patents funded by DOE in each time period. This figure follows a similar trend to Figure 1, with an initial period of active patenting in 1980-1984, followed by a relatively quiet period during the next time periods. The number of U.S. patents then increased sharply in 2005-2009, and continued to increase, peaking at 50 U.S. patents granted in 2015-2019 (32 of which are GTO-funded), even though data for this most recent time period are incomplete (see note below Figure 2).

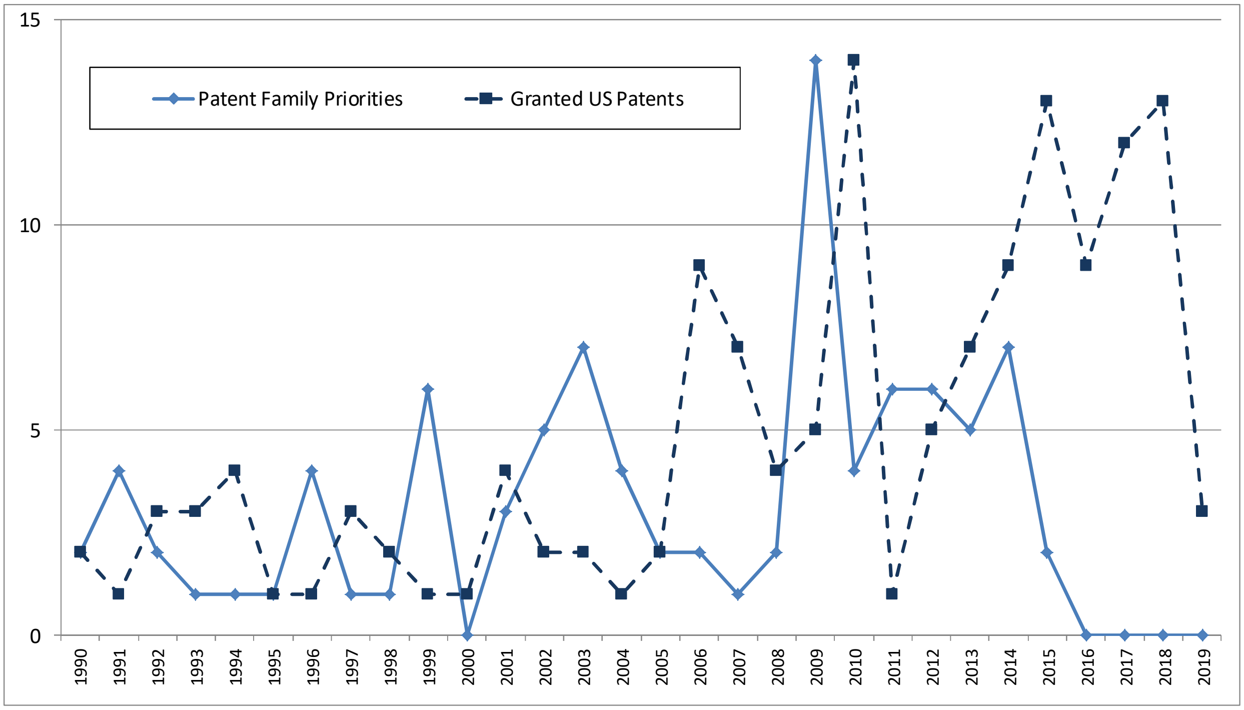
Figure 2 - Number of GTO/Other DOE-Funded Geothermal Energy Granted U.S. Patents by Issue Year (5-Year Totals)



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.

Comparing Figures 1 and 2 shows the effect of time lags in the patenting process, with many of the patent families with priority dates in 2000-2004, 2005-2009 and 2010-2014 (Figure 1) resulting in granted U.S. patents in 2005-2009, 2010-2014 and 2015-2019 (Figure 2). These time lags can also be seen in Figure 3, which shows geothermal energy patent family priority years alongside issue years for granted U.S. geothermal energy patents (in order to simplify the presentation, this figure focuses on the period from 1990 onwards, and data for GTO and Other DOE are combined). In this figure, peaks in patent families filed in 2003 and 2009 are associated with subsequent peaks in granted U.S. patents occurring in 2006 and 2010. More recently, patent family priorities filed in 2010-2014 resulted in corresponding increases in U.S. patents granted in 2014-2018 (note that, due to the primary data collection for this analysis ending in 2018, the number of U.S. patents declines sharply in 2019, and the number of families is zero).

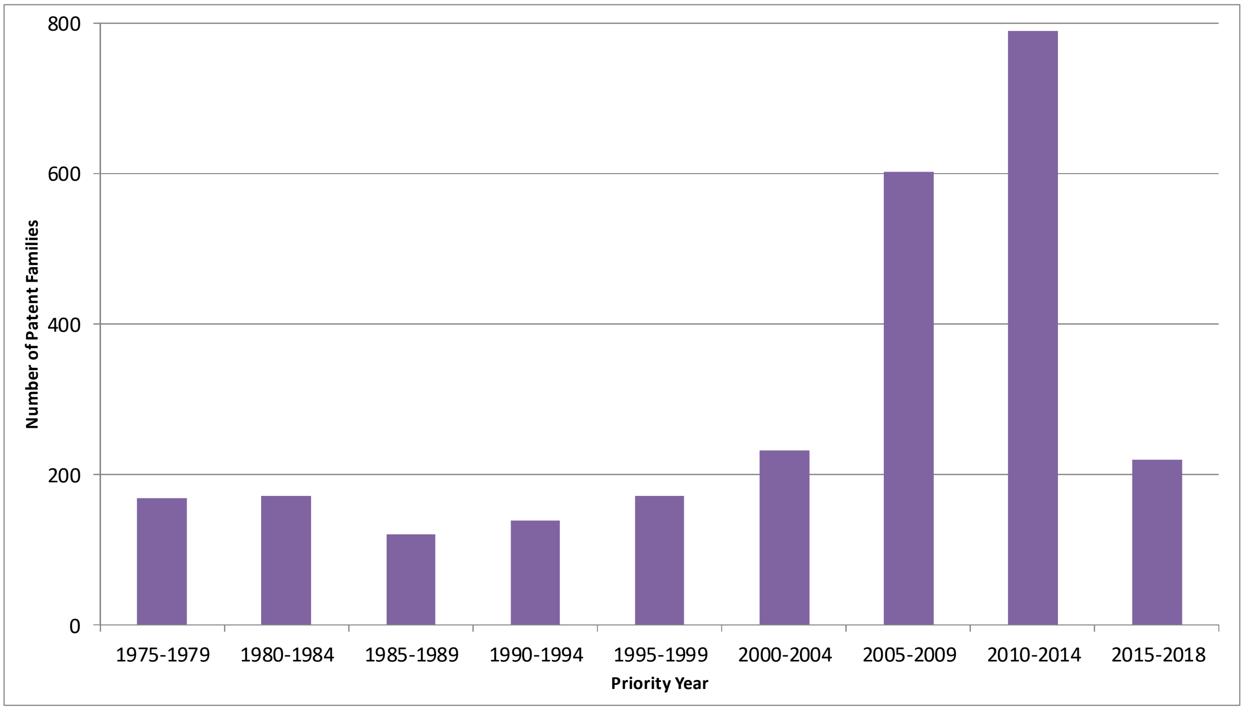
Figure 3 - Number of DOE-funded Geothermal Energy Patent Families (by Priority Year) and Granted U.S. Patents (by Issue Year)



Note: The data collection period for this analysis ended with 2018. Any 2019 patents 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.

Figures 1-3 focus on DOE-funded geothermal energy patent families. Figure 4 broadens the scope, and shows the overall number of geothermal patent families by priority year (based on USPTO, EPO, and WIPO filings). This chart reveals that overall geothermal energy patenting was relatively consistent in the earliest time periods, averaging around 35 patent families per year in both 1975-1979 and 1980-1984 (i.e. 170 families per 5-year period). The number of geothermal energy patent families then declined, before starting to grow from 1995 onwards, increasing in each time period through 2010-2014, with a total of 790 families filed in that period (i.e. more than five times as many patent families were filed in 2010-2014 as in 1990-1994). The number of patent families declined to 220 in 2015-2018, although data for this time period are incomplete. Comparing Figure 4 with Figure 1 suggests that the trend in DOE-funded (and GTO-funded) geothermal energy patenting is in line with the broader trend in this technology. Both figures show a relatively active period in the earliest years, followed by a quieter period, and then a sharp increase from 1995 onwards, peaking in 2010-2014.

Figure 4 - Total No. of Geothermal Energy Patent Families 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 - Percentage of Geothermal Energy Patent Families Funded by GTO/Other DOE by Priority Year

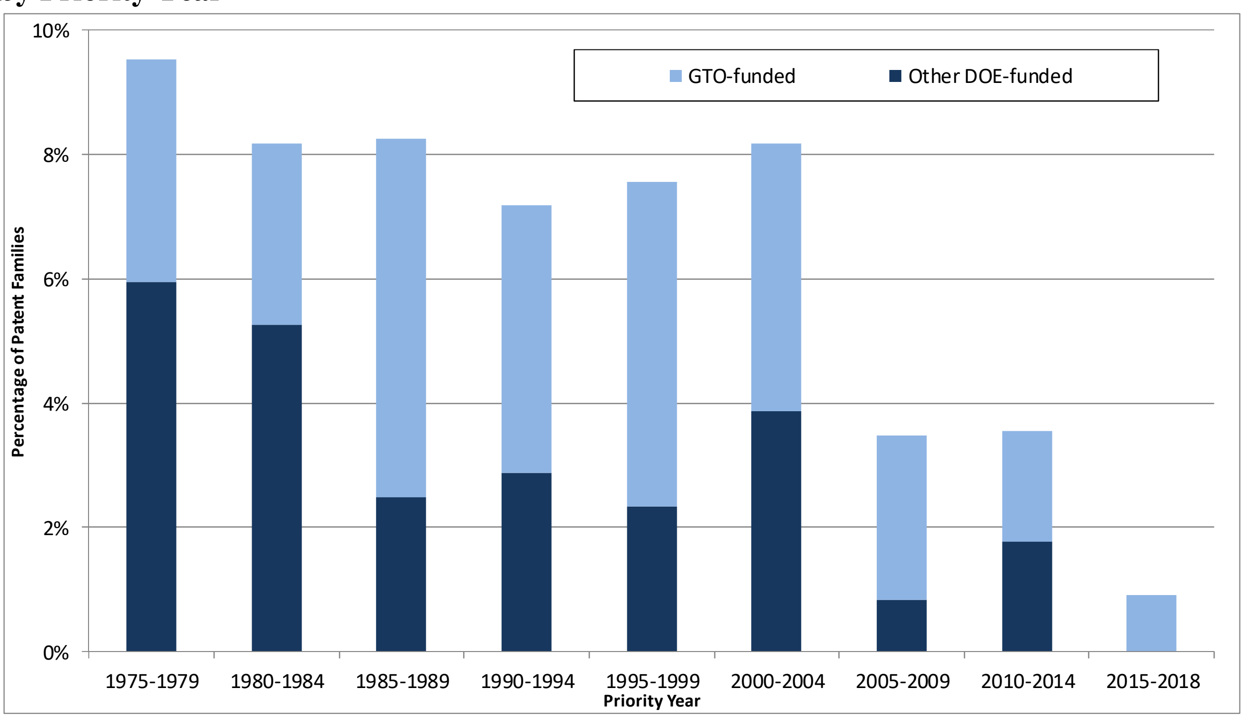


Figure 5 shows the percentage of geothermal energy patent families that were funded by DOE (GTO plus Other DOE) in each time period. This figure reveals that more than 7% of all geothermal patent families were funded by DOE in each time period through 2000-2004, with GTO-funded representing over half of these patent families from 1985 onwards. The percentage fell to just below 4% in 2005-2009 and 2010-2014. This coincided with the overall number of geothermal patent families increasing sharply (see Figure 4) as more organizations became involved in geothermal energy, so DOE was one of many sources of funding for geothermal research. Overall, 5.1% of geothermal patent families filed in 1976-2008 were funded by DOE (2.8% by GTO). Figure 5 thus suggests that GTO-funded (and Other DOE-funded) research played an important part in geothermal energy patenting, especially in earlier time periods.

Leading Geothermal Energy Assignees

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

Figure 6 – Top 10 Geothermal Energy Companies (based on number of patent families)

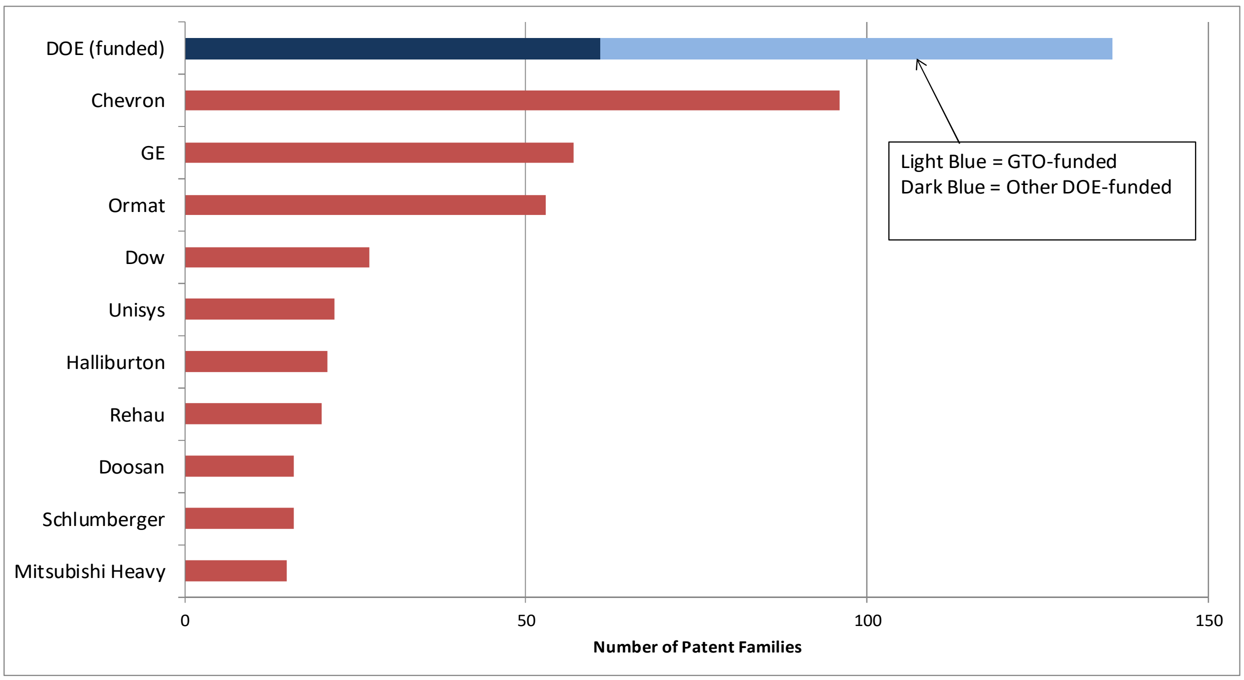


Figure 6 reveals that the portfolio of 136 DOE-funded geothermal patent families (75 GTO-funded; 61 Other DOE-funded) is larger than the geothermal patent portfolios associated with each of the ten largest companies. Chevron has the largest portfolio among these companies, containing 96 patent families, followed by General Electric (57 families) and Ormat (53 families). All of the other companies in Figure 6 have geothermal patent portfolios containing fewer than 30 patent families. In assessing the impact of GTO-funded and Other DOE-funded geothermal energy patents, versus the impact of the patent portfolios associated with the leading companies, we therefore take into account this difference in portfolio sizes. It is also interesting to note the geographical distribution of the leading geothermal energy companies in Figure 6. Out of these ten companies, six are based in North America, two in Asia and two in Europe.

It should be noted that there is some double-counting of patent families in Figure 6, specifically where innovations developed by a leading company were funded in whole or in part by GTO (or another office within DOE). For example, General Electric has one patent family was funded by GTO, while Unisys and Chevron have four and three families respectively that are Other DOE-funded. In Figure 6, these patent families are counted in both the GTO-funded or Other DOE-funded segment of the DOE column, 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 GTO/Other DOE-funded Geothermal Energy Patents

The DOE-funded geothermal energy patent portfolios are constructed somewhat differently from the portfolios of the top ten companies listed in Figure 6. Specifically, DOE's 136 patent families are those funded by DOE, but they are not necessarily assigned to the agency. For example, GTO (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 will be the respective DOE lab managers or companies (as in the case of the General Electric, Unisys and Chevron patent families discussed above).

Figure 7 shows the leading assignees on GTO-funded patent families. This chart is headed by Sandia Corporation with 14 patent families, through its management of Sandia National Laboratory. Simbol Materials is in second place in Figure 7, with 13 GTO-funded patent families, followed by DOE itself with 10 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 remaining organizations in Figure 7 include DOE lab managers, non-profits and companies, reflecting the range of organizations that have carried out GTO-funded geothermal energy research.

Figure 7 - Assignees with Largest No. of GTO-Funded Geothermal Energy Patent Families

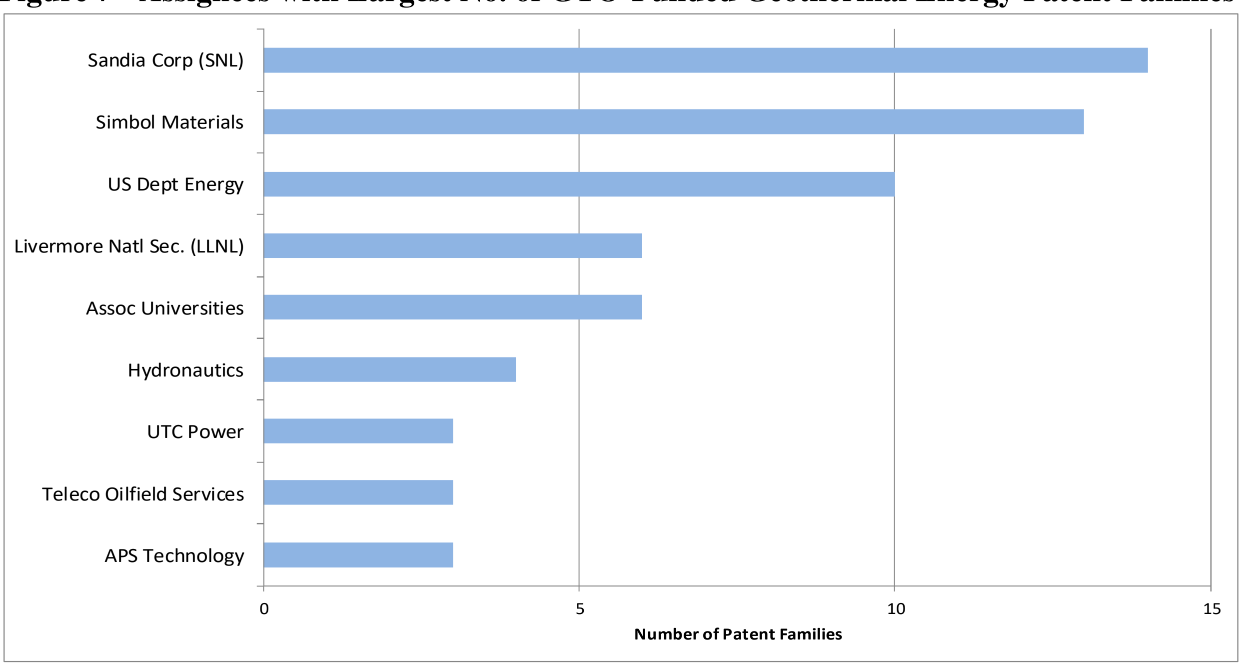
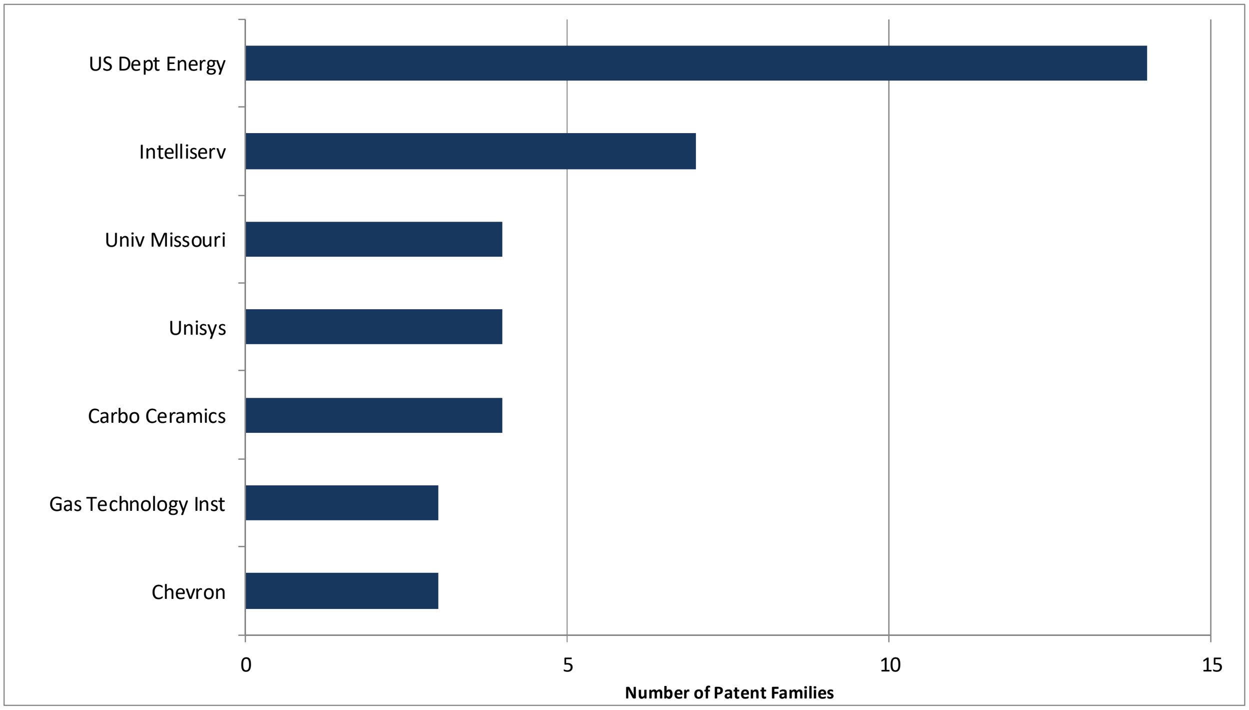


Figure 8 shows the leading assignees on Other DOE-funded geothermal energy patent families. This figure is headed by DOE with 14 patent families, followed by Intelliserv with seven families. The remaining organizations in Figure 8 include companies (Unisys, Carbo Ceramic, Chevron), universities (University of Missouri) and non-profits (Gas Technology Institute). All of these organizations have fewer than five Other DOE-funded patent families.

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



Distribution of Geothermal Energy Patents across Patent Classifications

We analyzed the distribution of GTO-funded geothermal energy U.S. patents across Cooperative Patent Classifications (CPCs).[8] We then compared this distribution to those associated with Other DOE-funded geothermal patents; geothermal patents assigned to the ten leading companies; and the universe of all geothermal patents. This analysis provides insights into the technological focus of GTO funding in geothermal energy, versus the focus of the rest of DOE, leading geothermal energy companies, and geothermal technology in general.

The results from this CPC analysis are shown in two separate charts, each from a different perspective. The first chart (Figure 9) is based on the seven CPCs that are most prevalent among GTO-funded geothermal energy patents. The purpose of this chart is thus to show the main focus areas of GTO-funded geothermal research, and the extent to which these areas translate to other portfolios (Other DOE-funded; leading geothermal companies; all geothermal energy). This figure shows that GTO-funded research includes relatively balanced coverage across the seven CPCs (which is not particularly surprising, since the GTO-funded patent portfolio forms the basis for the CPCs included in the chart). The most common CPC among GTO-funded

[8] 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.

geothermal energy patents is C22B 26, which appears on 16% of these patents. This CPC is related to obtaining alkali metals, such as lithium. It is one of a number of CPCs in Figure 9 related to lithium-based materials, including C01D 15 (Lithium compounds) and C01P 2006 (Inorganic compounds). These CPCs are present largely due to GTO's funding of research carried out by Simbol Materials into extracting lithium from geothermal brines. They are largely absent from the other portfolios in Figure 9. This figure also includes CPCs related to drilling rods and strings (E21B 17), surveying wells and boreholes (E21B 47) and obtaining materials from wells (E21B 43). Other DOE-funded patents have a notable presence in the latter two CPCs, with 40% of these patents in each of these CPCs. Meanwhile, the leading companies and geothermal patents overall are present primarily in the last of these CPCs (E21B 43).

Figure 9 - Percentage of Geothermal Energy U.S. Patents in Most Common Cooperative Patent Classifications (Among GTO-Funded Patents)

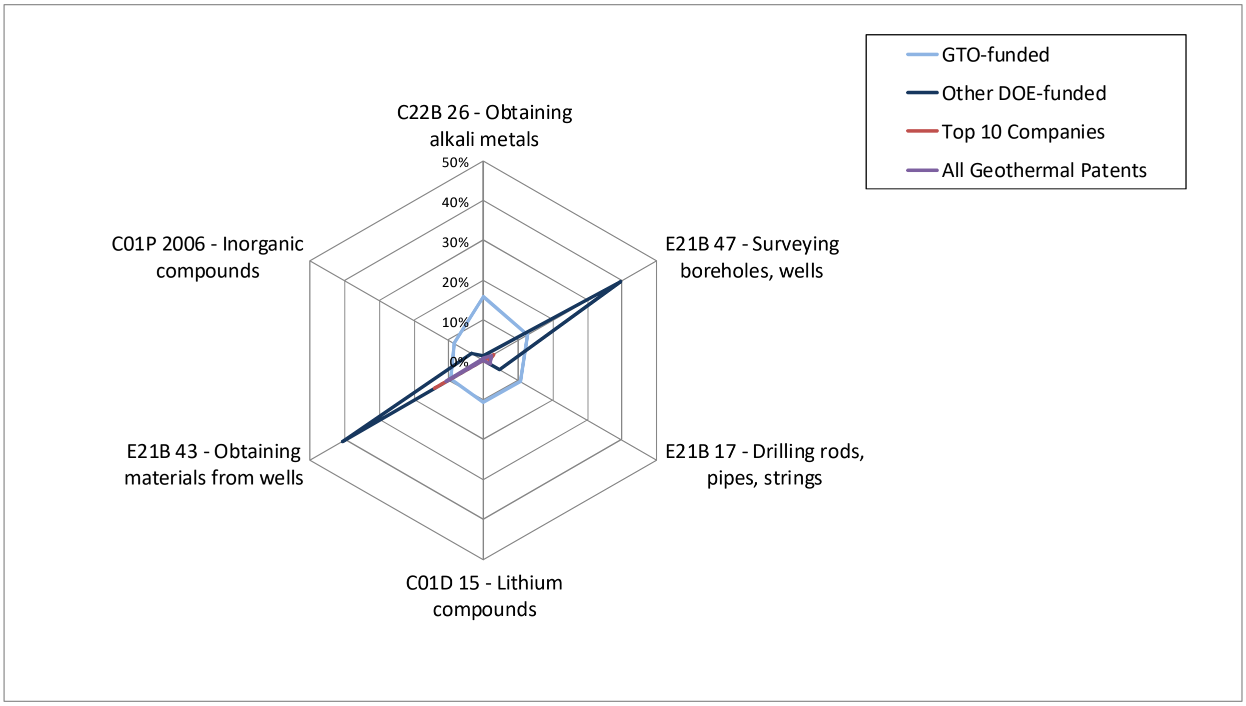


Figure 10 is similar to Figure 9, except that it is from the perspective of the most common CPCs among all geothermal energy patents. Hence, the purpose of this chart is to show the main research areas within geothermal energy as a whole, and how these areas are represented in selected geothermal portfolios (GTO-funded; Other DOE-funded; leading geothermal companies). The most common CPC among all geothermal patents is Y02E 10, which is concerned with renewable energy generation, including geothermal energy. Over 45% of all geothermal patents have this CPC attached (versus 30% for the leading companies, and 7% for GTO-funded and Other DOE-funded patents). Also prominent in Figure 10 is CPC F24T 10 (Geothermal collectors), with 30% of all geothermal patents having this CPC attached, a higher percentage than the other portfolios. Evaluating Figure 9 and Figure 10 together suggests that (leaving aside the specific funding of Simbol), GTO-funded geothermal research has focused more on physical aspects of downhole technology (surveying, drilling etc.), while geothermal patents in general have a greater concentration on generating energy from geothermal brines. This difference in focus suggests that, taking the period 1976-2018 as a whole, GTO-funded and

Other DOE-funded geothermal research helped fill a gap not addressed extensively by other organizations.

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

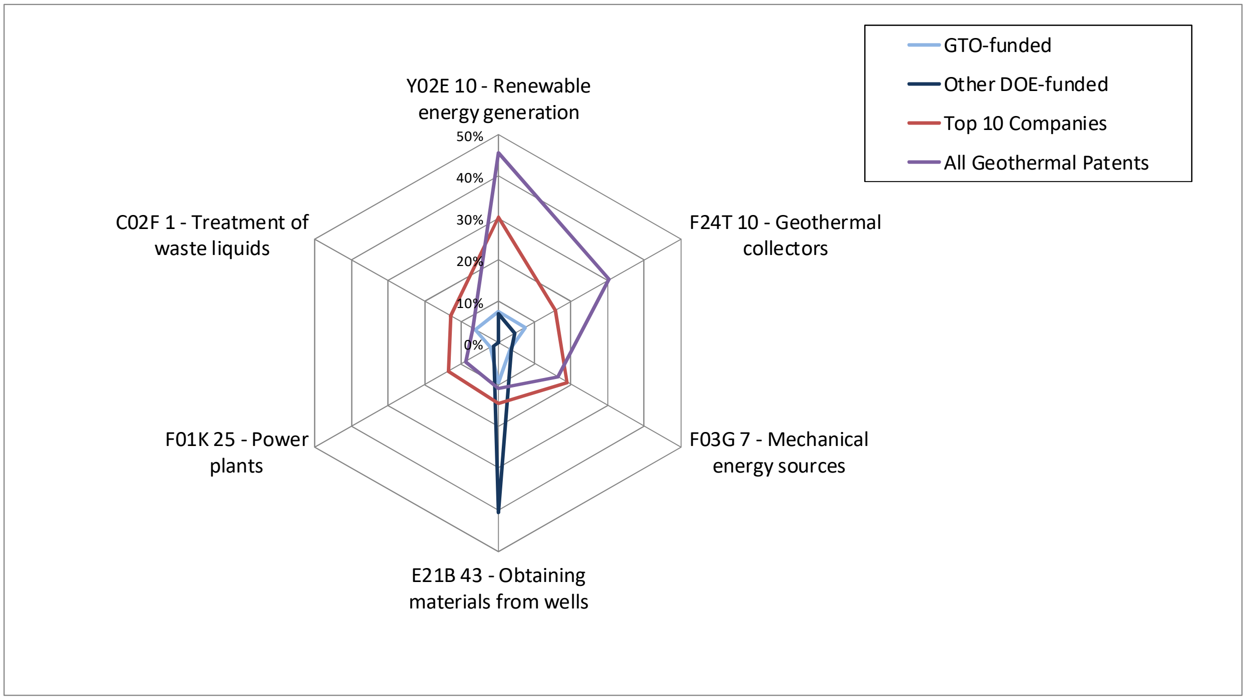


Figure 11 - Percentage of GTO-funded Geothermal Energy U.S. Patents in Most Common Cooperative Patent Classifications across Two Time Periods

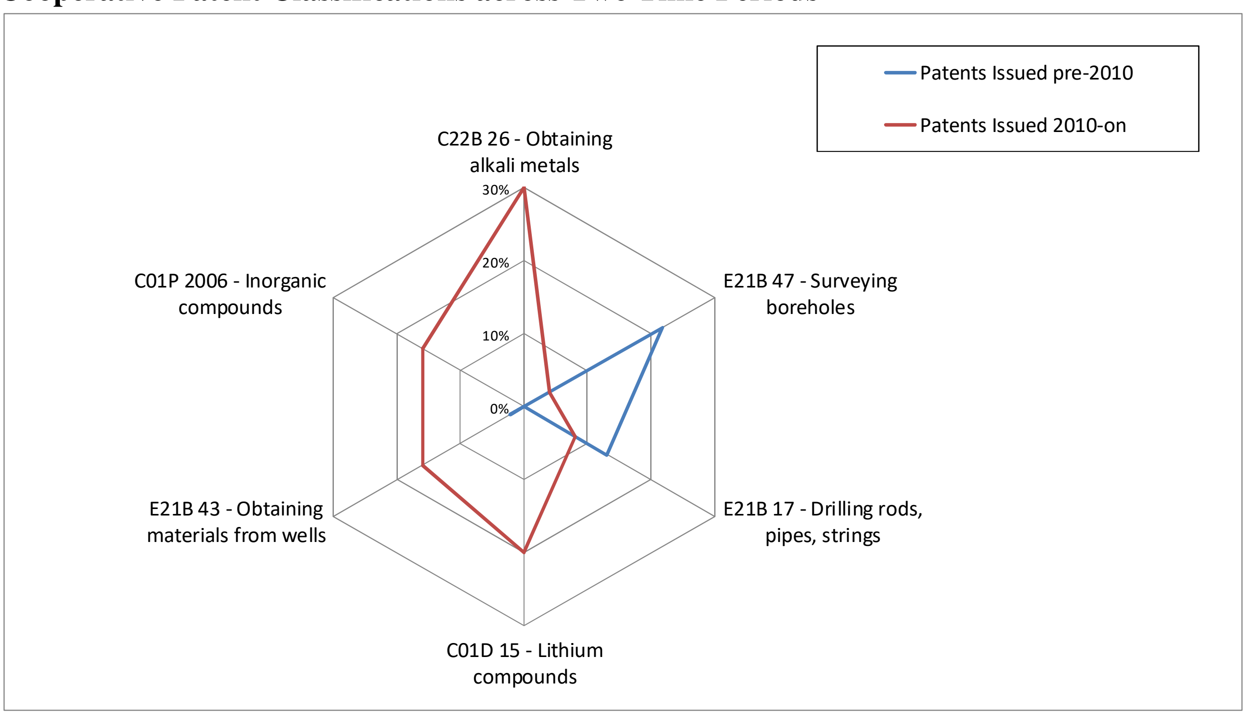


Figure 11 compares the CPC distribution of GTO-funded geothermal energy U.S. patents across two time periods – patents issued through 2009, and those issued from 2010 onwards (these dates are selected to divide the patents into two groups of approximately equal size). This figure reveals a distinct shift in focus between the two time periods. Patents from the earlier time period focus on downhole technologies, such as surveying boreholes (CPC E21B 47) and drilling components (CPC E21B 17). Meanwhile, patents from 2010 onwards have a much greater focus on technologies related to lithium compounds, reflecting GTO's funding of Simbol Materials.

Tracing Backwards from Geothermal Patents Owned by Leading Companies

This section reports the results of an analysis tracing backwards from geothermal energy patents owned by leading companies in this technology to earlier research, including that funded by DOE. 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 GTO-funded (and Other DOE-funded) research forms a foundation for subsequent innovations associated with leading geothermal energy companies. Second, we drill down to the level of individual patents, with a particular focus on GTO-funded geothermal energy patents. These patent-level results highlight specific GTO-funded patents that have influenced subsequent patents owned by leading companies. They also highlight which geothermal energy patents owned by these leading companies are linked particularly extensively to earlier GTO-funded research.

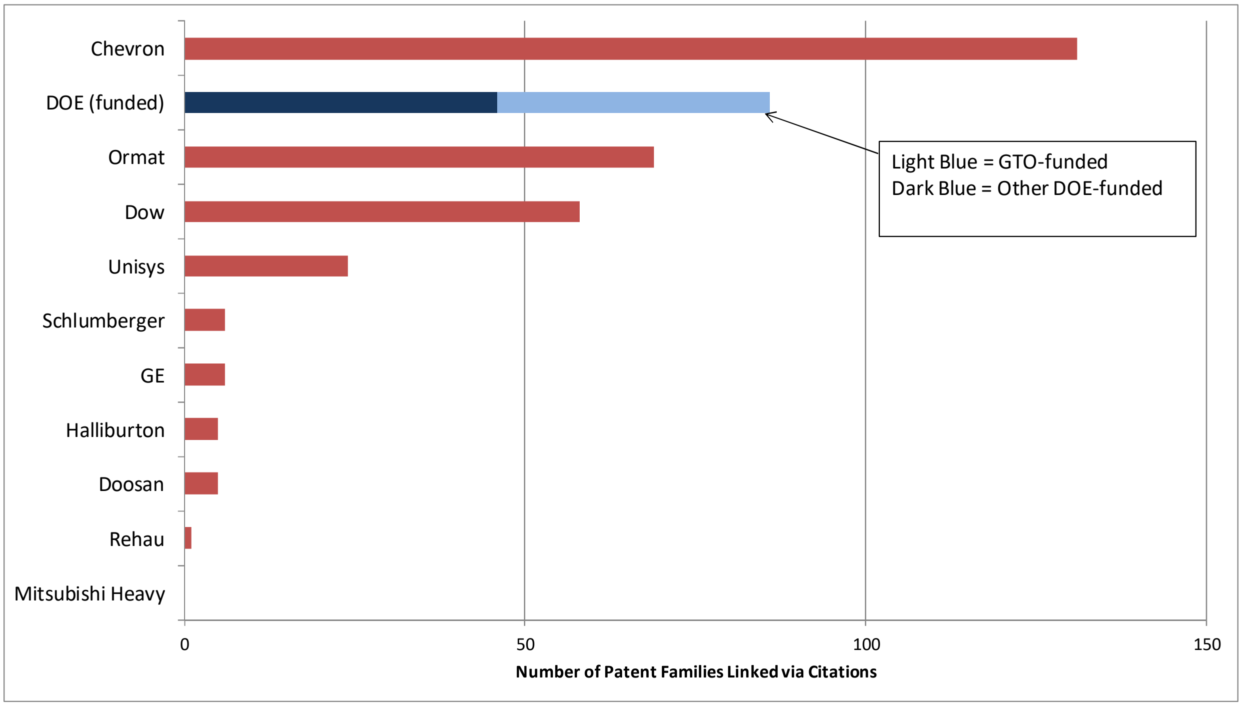
Organizational Level Results

In the organizational level results, we first compare the influence of GTO-funded and Other DOE-funded geothermal energy research against the influence of leading geothermal energy companies. We then look at which of these leading companies build particularly extensively on DOE-funded geothermal energy research.

Figure 12 compares the influence of DOE-funded geothermal energy research to the influence of research carried out by the top ten geothermal energy companies. Specifically, this figure shows the number of geothermal energy patent families owned by the leading companies that are linked via citations to earlier geothermal energy 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 geothermal technology.[9]

[9] This figure compares the influence of patents *funded* by GTO/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 6, there is some double-counting in Figure 12 and Figure 13, as some patent families assigned to General Electric, Chevron and Unisys were funded by DOE. Also, in Figures 12 and 14-16, leading company patent families linked to both GTO-funded and Other DOE-funded patents are allocated to the GTO-funded segment of the DOE column, in order to avoid double-counting these families.

Figure 12 - Number of Leading Company Geothermal Energy Patent Families Linked via Citations to Earlier Geothermal Energy Patents from each Leading Company
e.g. 86 leading company families are linked to earlier GTO/Other DOE-funded families



In total, 86 leading company geothermal energy patent families (i.e. 25% of these 343 families) are linked via citations to earlier DOE-funded geothermal energy patents, out of which 40 are linked to GTO-funded geothermal energy patents. This finding puts DOE-funded patents in second place in Figure 12, behind Chevron (with 131 leading company patent families linked to its earlier patents). As such, it suggests that the leading companies have built extensively on the portfolios of GTO-funded and Other DOE-funded geothermal patents. That said, it should be noted that Figure 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 more leading company patent families are linked via citations to DOE-funded patents than to other leading companies, since the DOE-funded portfolio is much larger, and so contains more patents to be cited as prior art by subsequent patents.

Figure 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 geothermal energy patent families are each linked to an average of 0.63 patent families assigned to the leading companies. This puts DOE near the center of the distribution in Figure 13, which is headed by Dow Chemical, whose geothermal patent families are each linked to an average of over two families owned by the leading companies. It suggests that the prominence of DOE in Figure 12 is largely due to its portfolio size, with its influence being around the average once size is taken into account.

Figure 13 – Average Number of Leading Company Geothermal Energy Patent Families Linked via Citations to Geothermal Energy Families from Each Leading Company
e.g. on average, each DOE-funded family is linked to 0.63 leading company patent families

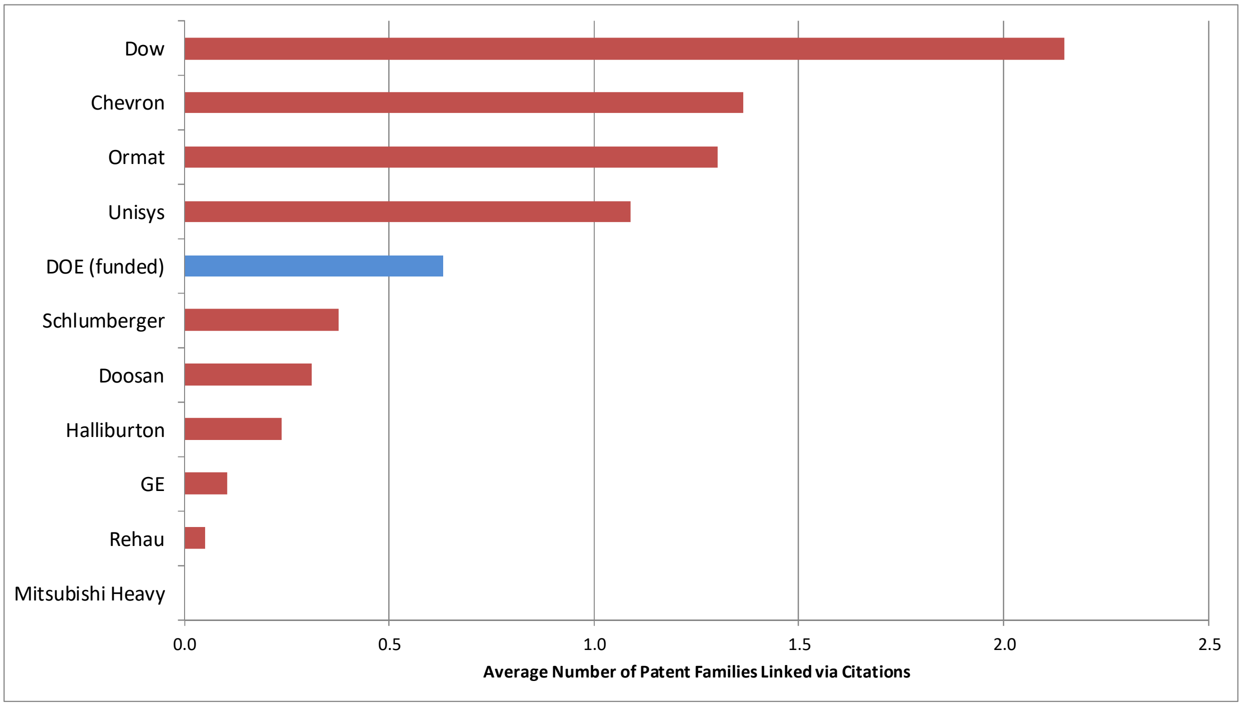
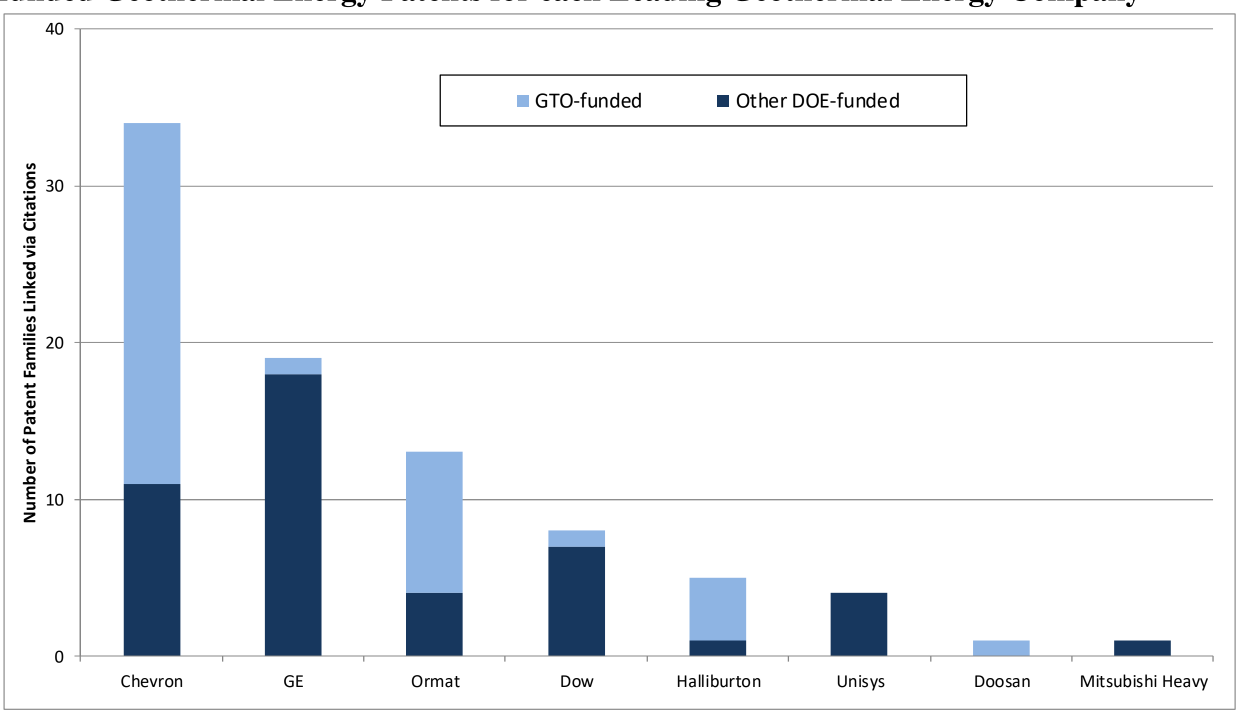


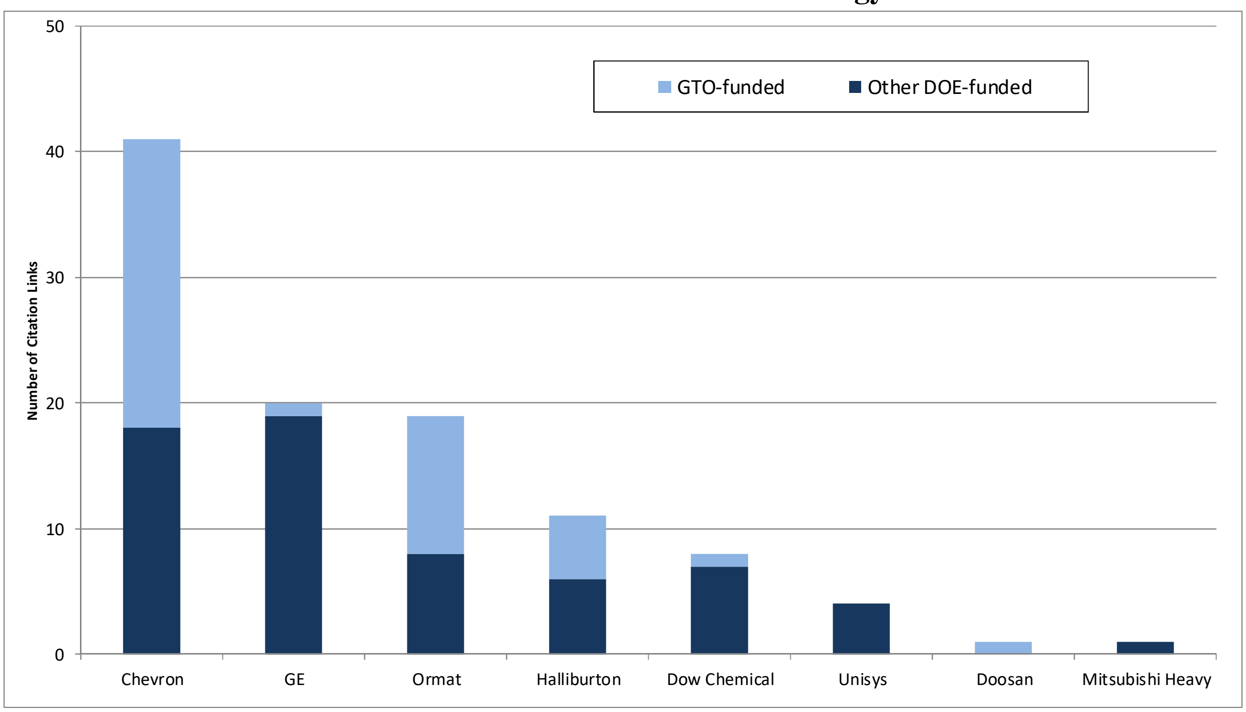
Figure 14 – Number of Patent Families Linked via Citations to Earlier GTO/Other DOE-funded Geothermal Energy Patents for each Leading Geothermal Energy Company



Figures 14 through 16 examine which of the leading companies build particularly extensively on earlier DOE-funded patents. Figure 14 shows how many geothermal energy patent families owned by each of the leading companies are linked via citations to earlier DOE-funded patents. This figure reveals that, out of the ten leading geothermal energy companies, eight (i.e. all except Schlumberger and Rehau) have at least one patent family linked to earlier DOE-funded geothermal patents. Chevron is at the head of Figure 14, with 34 patent families linked via citations to earlier DOE-funded geothermal energy patents, 23 of which are linked to GTO-funded patents. General Electric is in second place in this figure, with 19 patent families linked via citations to DOE (one of which is linked to GTO), followed by Ormat (13 families linked to DOE; 9 to GTO) and Dow (8 families linked to DOE; 1 to GTO).

Figure 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 14, since a single patent family may be linked to multiple earlier DOE-funded patents. The same three companies are at the head of Figure 15 – Chevron, General Electric and Ormat – reinforcing their close links to earlier DOE-funded geothermal energy research. Halliburton moves ahead of Dow in fourth place in this figure, although the numbers of citation links are relatively low.

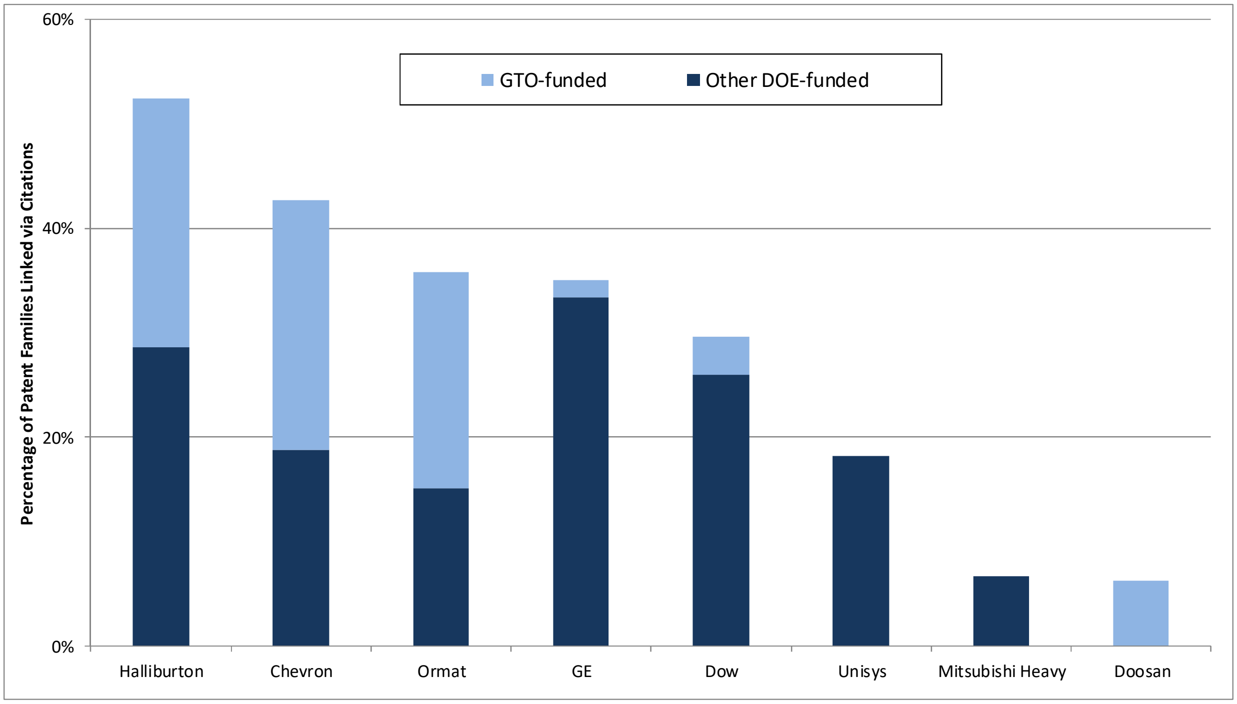
Figure 15 - Number of Citation Links from Leading Geothermal Energy Company Patent Families to Earlier GTO/Other DOE-funded Geothermal Energy Patents



There is an element of portfolio size bias in the patent family counts in Figures 14 and 15. Companies with larger geothermal energy patent portfolios are likely to have more patent families linked to DOE, simply because they have more families overall. Figure 16 accounts for this portfolio size bias by calculating the percentage of each leading company's geothermal energy patent families that are linked via citations to earlier DOE-funded geothermal energy 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 16 further emphasizes the extensive citation links between DOE-funded geothermal patents and subsequent patent families owned by Chevron, General Electric and Ormat. More than one-third of each of these companies' geothermal patent families are linked via citations to earlier DOE-funded geothermal patents. That said, Figure 16 is headed by Halliburton, with over half of its geothermal families (11 out of 21) linked via citations to earlier DOE-funded patents.

Figure 16 - Percentage of Leading Geothermal Energy Company Patent Families Linked via Citations to Earlier GTO/Other DOE-funded Geothermal Energy 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 geothermal energy patent families (in particular GTO-funded families) that have had a strong influence on subsequent geothermal energy patents owned by leading companies in this technology. Looking in the opposite direction, it also identifies individual geothermal energy patents owned by leading companies that have extensive links to earlier GTO-funded research.

Table 5 shows the GTO-funded geothermal energy patent families linked via citations to the largest number of subsequent patent families owned by leading companies in this technology. As such, the patent families in this table represent GTO-funded technologies that are linked to subsequent innovations associated with leading companies in the geothermal energy industry.

The GTO-funded patent family linked to the most leading company families was filed in 1980 and assigned to DOE. This patent family (whose representative patent[10] is US #4,328,106)

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

describes a method for reducing silica scaling in geothermal systems. It is linked via citations to 22 subsequent patent families assigned to the leading companies, including Chevron, Dow and Halliburton families related to scale reduction and families describing geothermal power plants assigned to Ormat. The patent family in second place in Table 5 (representative patent US #4,358,930) was also filed in 1980 and assigned to DOE. This family describes Rankine cycle power plants, and is linked to six patent families owned by the leading companies, notably power generation families assigned to Ormat. Other patent families in Table 5 include a UTC Power family for a Rankine cycle, an MRIGlobal (National Renewable Energy Laboratory) family outlining condenser apparatus for a geothermal power plant, and a DOE family related to grouts for geothermal heat pumps.

Table 5 – GTO-Funded Geothermal Energy Patent Families Linked via Citations to Most Subsequent Leading Company Geothermal Energy Patent Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
22572028	4328106	1980	22	US Dept Energy	Method for inhibiting silica precipitation and scaling in geothermal flow systems
22585231	4358930	1980	6	US Dept Energy	Method of optimizing performance of Rankine cycle power plants
46204872	6880344	2002	5	UTC Power	Combined Rankine and vapor compression cycles
25240917	5925291	1997	4	MRIGlobal (NREL)	Method and apparatus for high-efficiency direct contact condensation
23048583	6251179	1999	3	US Dept Energy	Thermally conductive cementitious grout for geothermal heat pump systems

Table 5 lists GTO-funded patents linked to large numbers of subsequent geothermal energy patent families owned by leading companies. Table 6 looks in the opposite direction, and lists the three geothermal energy patent families owned by leading companies that are linked to multiple earlier families funded by GTO (each of these leading companies is linked to two earlier GTO-funded families). Two of the three patent families in Table 6 are assigned to Ormat and describe geothermal power plants. These two Ormat families (representative patents US #5,400,598 and US #5,867,988) were filed in the mid-1990s, and are both linked via citations to the patent families assigned to DOE highlighted above at the head of Table 5. The third patent family in Table 6 (representative patent US #9726157) is newer, having been filed in 2012. This family is assigned to Halliburton, and describes an enhanced geothermal system (EGS). It is linked via citations to two earlier GTO-funded patent families related to geothermal boilers and reducing vibration in drill strings.

Table 6 - Leading Company Geothermal Energy Patent Families Linked via Citations to Largest Number of GTO-Funded Geothermal Energy Patent Families

Patent Family #	Representative Patent #	Priority Year	# GTO Fams	Assignee	Title
22018744	5400598	1993	2	Ormat Technologies	Method and apparatus for producing power from two-phase geothermal fluid
49551089	9726157	2012	2	Halliburton	Enhanced geothermal systems and methods
26878025	5867988	1994	2	Ormat Technologies	Geothermal power plant and method for using the same

We also identified high-impact geothermal energy patents owned by leading companies that have citation links back to GTO-funded patents.[11] The idea is to highlight important technologies owned by leading companies that are linked to earlier geothermal energy research funded by GTO. Table 7 lists geothermal energy patents owned by leading companies that have Citation Index values of 1.75 or over (i.e. they have been cited at least 75% more frequently as expected), and are linked via citations to earlier GTO-funded geothermal energy patents. The patents are listed in descending order based on their Citation Index.

The patent at the head of Table 7 (US #5,497,624) is assigned to Ormat and describes a geothermal power plant. Since this Ormat patent was issued in 1996, it has been cited as prior art by 55 subsequent patents, which is more than two-and-a-half times as many citations as expected given its age and technology. In turn, this patent is linked via citations to an earlier GTO-funded patent family for Rankine cycle power plants, which was highlighted earlier in Table 5. The second patent in Table 7 (US #4,830,766) is assigned to Chevron and describes reducing agents for controlling scaling in geothermal brines. This patent is linked via citations to the GTO-funded patent family for scaling reduction listed at the head of Table 5. In turn, the Chevron patent has been cited as prior art by 48 subsequent patents, more than twice as many citations as expected. It is the first of a number of Chevron patents in Table 7 related to scale reduction, all of which are linked to the same earlier GTO-funded family, as is the Dow family in this table.

Table 7 - Highly Cited Leading Company Geothermal Energy Patents Linked via Citations to Earlier GTO-funded Geothermal Energy Patents

Patent	Issue Year	# Cites Received	Citation Index	Assignee	Title
5497624	1996	55	2.66	Ormat Technologies	Method of and apparatus for producing power using steam
4830766	1989	48	2.33	Chevron Corp	Use of reducing agents to control scale deposition from high temperature brine
4537684	1985	44	2.24	Chevron Corp	Control of metal containing scale deposition from high temperature brine
5277823	1994	41	2.06	Dow Chemical	Silica scale inhibition
4765913	1988	36	1.79	Chevron Corp	Process for removing silica from silica-rich geothermal brine
4756888	1988	20	1.76	Chevron Corp	Recovery of silver-containing scales from aqueous media

[11] 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 F24T 10 (Geothermal collectors) 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 a patent has been cited 50% more frequently than expected. Meanwhile a Citation Index of 0.7 reveals 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 been cited less frequently than expected. Note that the Citation Index is calculated for U.S. patents only, since citation rates differ across patent systems.

While the patent-level results focus on GTO-funded geothermal energy patent families, we also identified Other DOE-funded geothermal energy families linked via citations to the largest number of patent families owned by the leading companies. These Other DOE-funded families are shown in Table 8. It should be noted that all of these patent families are marked as “unknown” for GTO funding, rather than being marked as definitely not GTO-funded. As such, while they are defined as Other DOE-funded, some may in fact have been funded by GTO.

Table 8 - Other DOE-Funded Geothermal Energy Patent Families Linked via Citations to Most Subsequent Leading Company Geothermal Energy Families

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
23605865	4489563	1982	18	Unassigned (Alexander Kalina)	Generation of energy
21718476	4196183	1979	14	US Dept Energy	Process for purifying geothermal steam
24359727	5685362	1996	4	Univ California (LANL)	Storage capacity in hot dry rock reservoirs
23935596	3938334	1974	4	Unisys Corp	Geothermal energy control system and method
26929210	4424858	1981	3	US Dept Energy	Apparatus for recovering gaseous hydrocarbons from hydrocarbon containing solid hydrates
22661601	4342197	1980	3	Unisys Corp	Geothermal pump down-hole energy regeneration system

There are two patent families in Table 8 that stand out in terms of the number of subsequent leading company families linked to them via citations. The first is a 1982 patent family (representative patent US #4,489,563) originally assigned to its inventor, Alexander Kalina (and subsequently reassigned, ultimately to Wasabi Energy). This family describes the Kalina cycle for energy generation. It is linked via citations to 18 subsequent families assigned to the leading companies, notably General Electric and Ormat families describing geothermal power plants, the former specifically based on the Kalina cycle. The second patent family in Table 8 (representative patent US #4,196,183) is assigned to DOE and describes a method for reducing hydrogen sulfide in geothermal steam. It was filed in 1979, and is linked via citations to 14 subsequent patent families owned by the leading companies. These include Chevron and Dow patent families describing treatment of geothermal brines. Table 8 does include one somewhat more recent patent family. This family (representative patent US #5,685,362) was filed in 1996 and assigned to the University of California, through its management of Los Alamos National Laboratory. It describes a method for extracting thermal energy from hot dry rocks, and is linked via citations to four subsequent leading company patent families, including families assigned to Chevron, Halliburton, Mitsubishi Heavy Industries and Ormat.

Overall, the backward tracing element of the analysis suggests that the portfolios of GTO-funded and Other DOE-funded geothermal energy patents have had an important influence on subsequent innovations associated with the leading geothermal energy companies. This influence can be seen both over time and across technologies, with a various DOE-funded patent families linked via citations to subsequent patents assigned to a number of the leading companies.

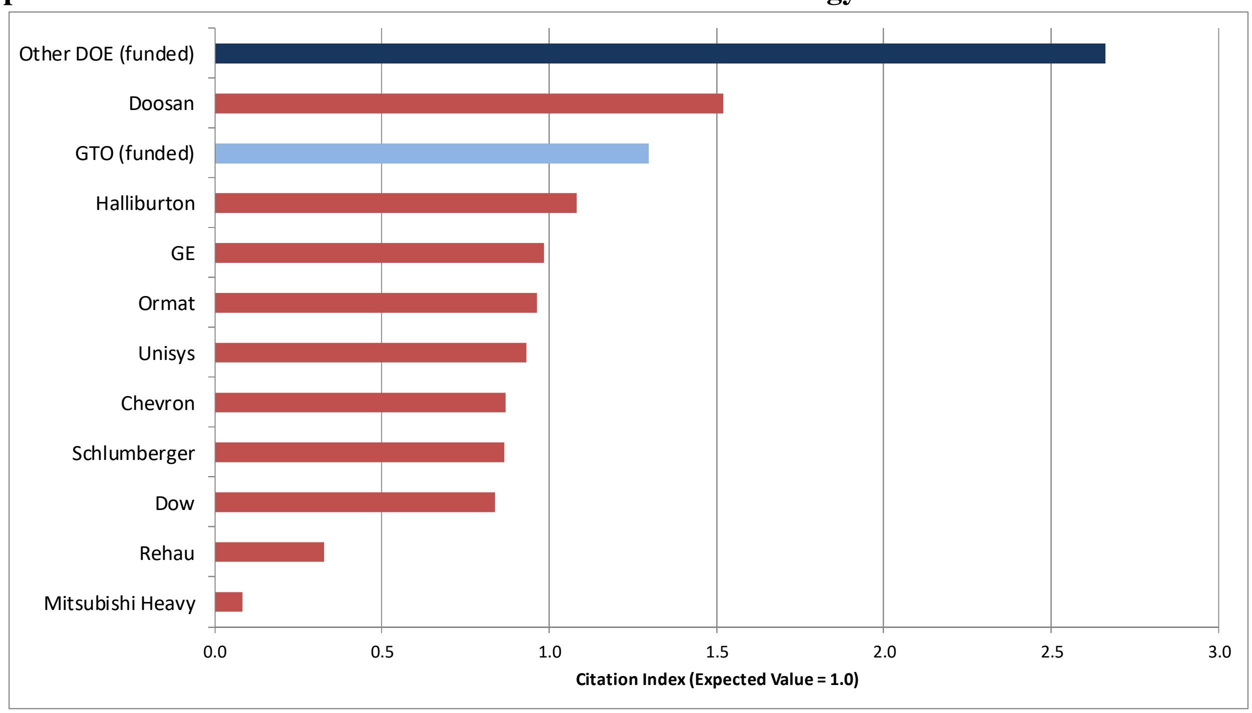
Tracing Forwards from DOE-funded Geothermal Energy Patents

The previous section of the report examined the influence of DOE-funded geothermal energy research upon technological developments associated with leading geothermal energy 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 GTO-funded (and Other DOE-funded) geothermal energy patents, and tracing forwards in time through two generations of citations. Hence, while the previous section of the report focused on DOE's influence upon a specific patent set (i.e. patents owned by leading geothermal energy companies), this section of the report examines on the broader influence of GTO-funded (and Other DOE-funded) geothermal energy research, both within and beyond the geothermal energy industry. Also, in order to avoid repeating earlier results, the forward tracing concentrates primarily on patents that are linked to DOE-funded geothermal energy research, but are not owned by the leading geothermal energy companies.

Organizational Level Results

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

Figure 17 – Average Citation Index for Leading Companies' Geothermal Energy Patents, plus GTO-funded and Other DOE-funded Geothermal Energy Patents

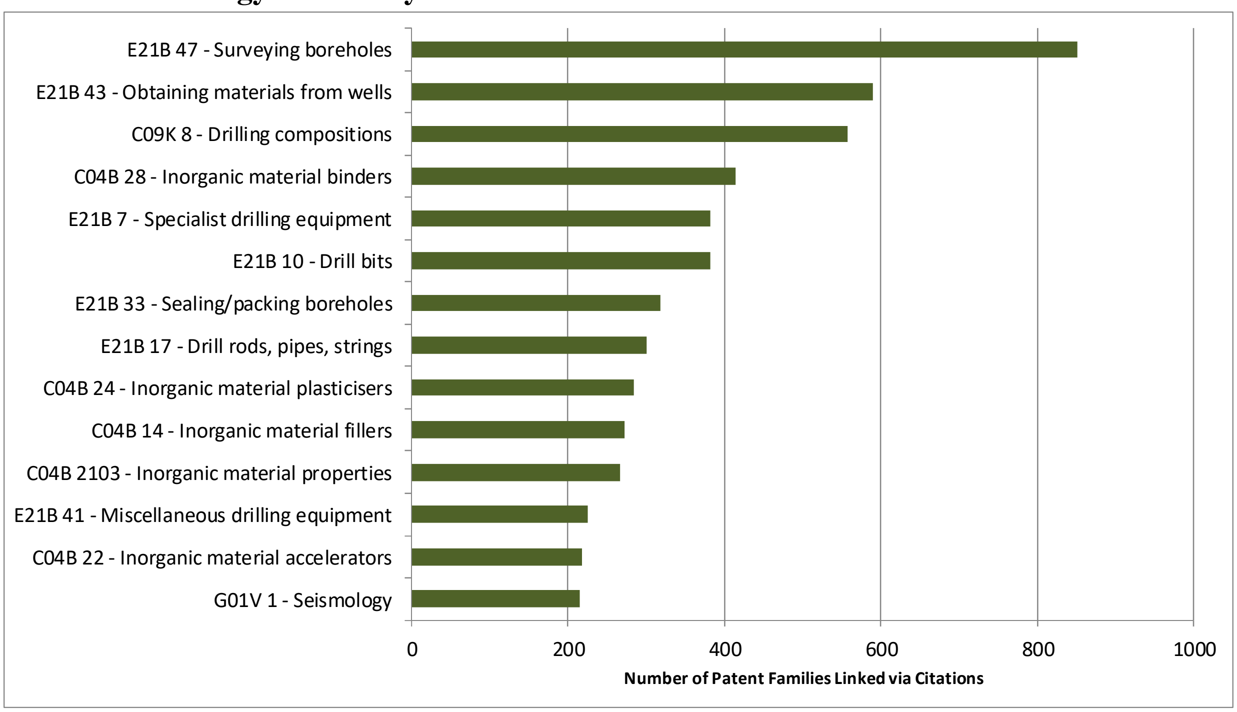


This figure reveals that both the GTO-funded and Other DOE-funded geothermal energy patent portfolios have high average Citation Index values compared to those of the ten leading companies. Other DOE-funded patents have a Citation Index of 2.66 (showing they have been cited more than two-and-a-half times as frequently as expected), which is higher than all of the leading companies. The Citation Index for GTO-funded geothermal energy patents is lower at 1.30, but this still means that these patents have been cited 30% more frequently than expected. This puts GTO-funded patents in third place in Figure 17, behind Other DOE and Doosan (which has a Citation Index of 1.52).

The Citation Index measures the overall influence of the DOE-funded geothermal energy patent portfolios, but does not necessarily address the breadth of this influence across technologies. To analyze this question, we therefore identified the Cooperative Patent Classifications (CPCs) of the patent families linked via citations to earlier DOE-funded geothermal patent families.[12] These CPCs reflect the influence of DOE-funded research across technologies.

Figure 18 shows the CPCs with the largest number of patent families linked to GTO-funded geothermal energy patents. Typically, a figure such as this shows CPCs in two different colors – i.e. those related to geothermal technology and those beyond this technology. The former represent the influence of GTO-funded patents on geothermal energy itself, while the latter represent spillovers of the influence of GTO-funded geothermal energy research into other technology areas.

Figure 18 - Number of Patent Families Linked via Citations to Earlier GTO-Funded Geothermal Energy Patents by CPC



In Figure 18, all of the CPCs are shown in a single color since, as noted earlier, there are many overlaps in terms of CPCs between geothermal patents and the much larger group of patents related to oilfield technologies. These include CPCs related to technologies such as drilling

[12] 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 via citations to earlier DOE-funded geothermal energy patent families.

components, borehole surveying, and well materials, which cannot be defined entirely as within or outside geothermal technology. For example, the CPC at the head of Figure 18 (E21B 47) is related to surveying wells and boreholes. There are 851 patent families in this CPC that are linked via citations to earlier GTO-funded geothermal patent families. It is followed by CPC E21B 43 (Obtaining materials from wells) and C09K 8 (Compositions for drilling boreholes), with 499 and 456 families respectively. Overall, the CPCs in Figure 18 are concerned primarily with downhole technologies, rather than methods for treating geothermal brines and generating energy from these brines.

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

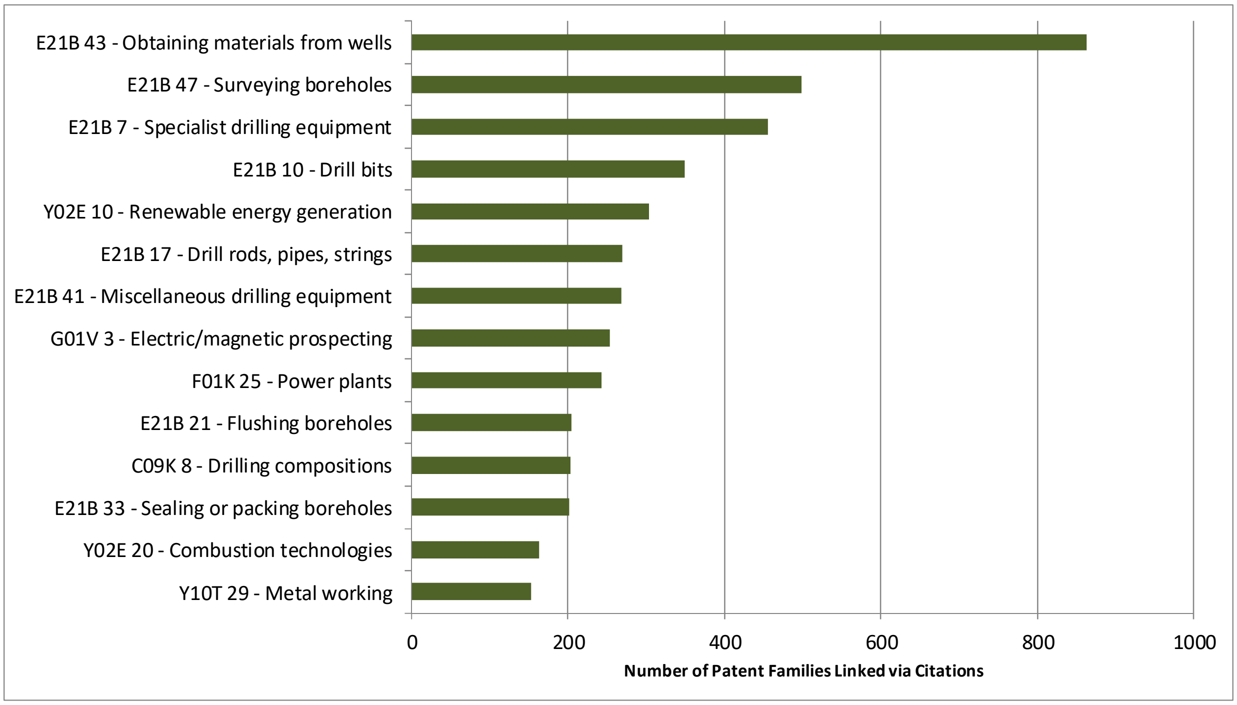


Figure 19 is similar to Figure 18, but is based on patent families linked to Other DOE-funded geothermal energy patents, rather than to GTO-funded geothermal energy patents. Again, all of the CPCs in this figure are shown in a single color, given the difficulty of defining these CPCs as entirely within or outside geothermal technology. This figure again includes numerous CPCs related to downhole technologies such as drilling and surveying. That said, it does also feature CPCs related to renewable energy generation (Y02E 10) and power plants (F01K 25).

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

Royal Dutch Shell is at the head of Figure 20, with 122 patent families linked via citations to earlier GTO-funded geothermal energy patents. These Shell patent families cover a range of technologies related to oil and gas extraction, and are linked to a range of earlier GTO-funded patents, notably Sandia patents for downhole telemetry systems (e.g. US #5,363,095). ExxonMobil is in second place in Figure 20, with 117 patent families linked via citations to earlier GTO-funded patents. Many of these ExxonMobil families describe drilling techniques and telemetry systems, and are linked via citations to earlier GTO-funded geothermal patents related to downhole drilling techniques and borehole materials. These are examples of the influence of GTO-funded geothermal patents extending into oilfield technologies, a link further emphasized by the fact that the five companies at the head of Figure 20 are all involved in the oil and gas industry. Figure 20 also includes companies from other industries – notably Siemens, Cummins and Ford – that have waste heat recovery and energy generation patent families linked to earlier GTO-funded patents. These are examples of GTO-funded geothermal energy research influencing subsequent developments beyond both geothermal and oilfield technologies.

Figure 20 - Organizations with Largest Number of Patent Families Linked via Citations to GTO-funded Geothermal Patents (excluding leading geothermal energy companies)

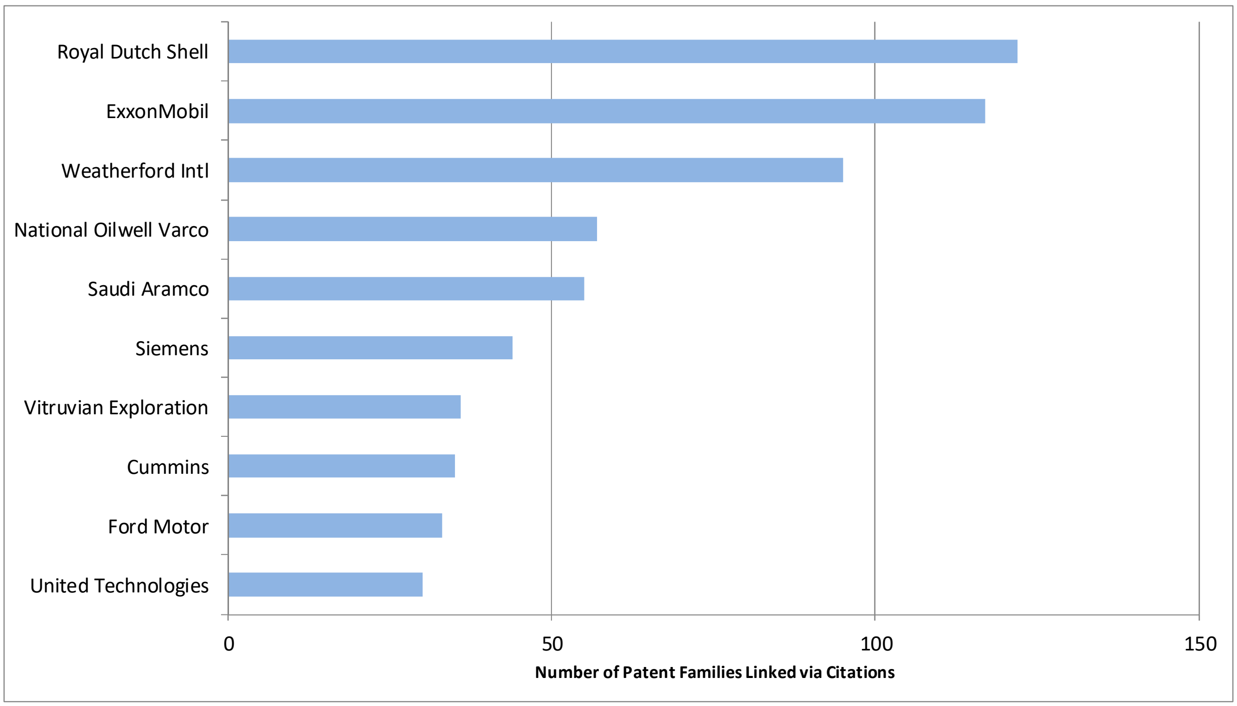
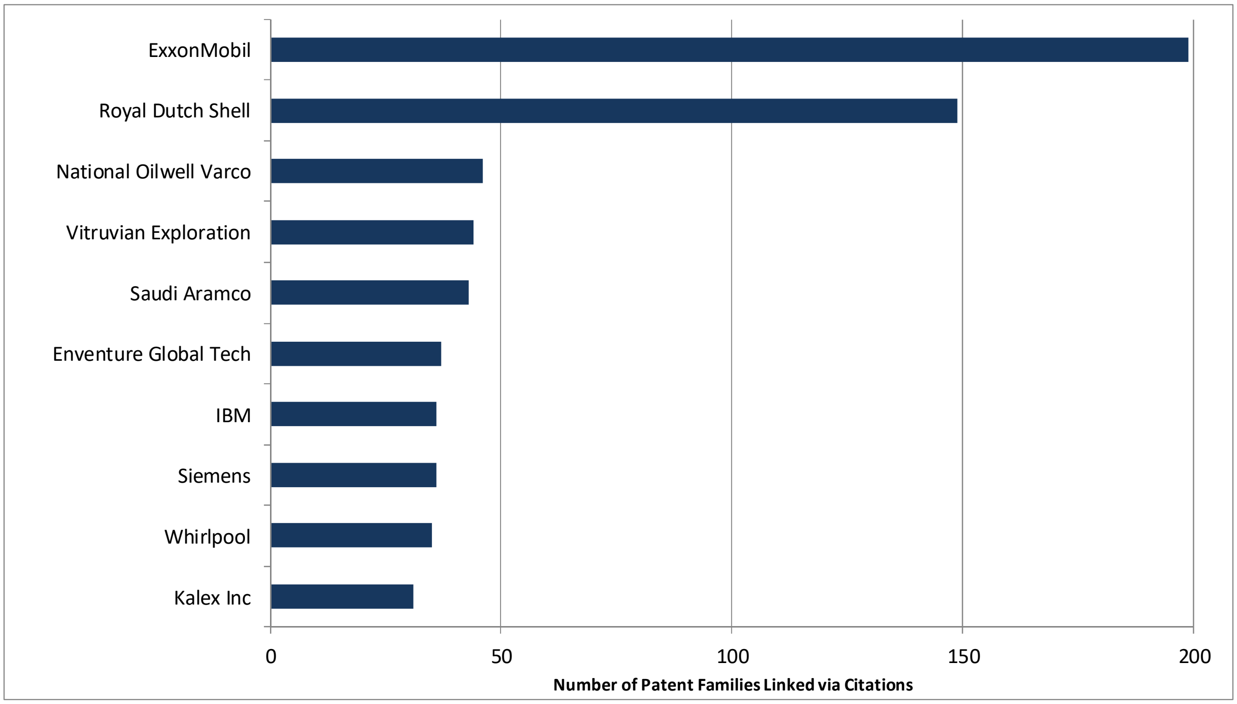


Figure 21 shows the organizations with the largest number of patent families linked to earlier Other DOE-funded geothermal energy patents. This figure is again dominated by oil and gas companies, reinforcing the extensive links between DOE-funded geothermal research and subsequent innovations in oilfield technologies. ExxonMobil and Shell are at the head of Figure 21, with 199 and 149 patent families linked via citations to earlier Other DOE-funded geothermal patents respectively. Both of these companies have patent families related to a range of oilfield technologies (including oil shale extraction, in situ hydrocarbon conversion, and drilling components) that are linked via to earlier Other DOE-funded patents for drilling techniques and materials processing. Other non-oilfield companies in Figure 21 include IBM (with patents related to audio-video linked to earlier Intelliserv downhole communications patents) and Whirlpool (with refrigeration patents linked to earlier DOE patents for cooling borehole electrical components). These are again examples of DOE-funded geothermal research influencing innovations beyond geothermal and oilfield technologies.

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



Patent Level Results

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

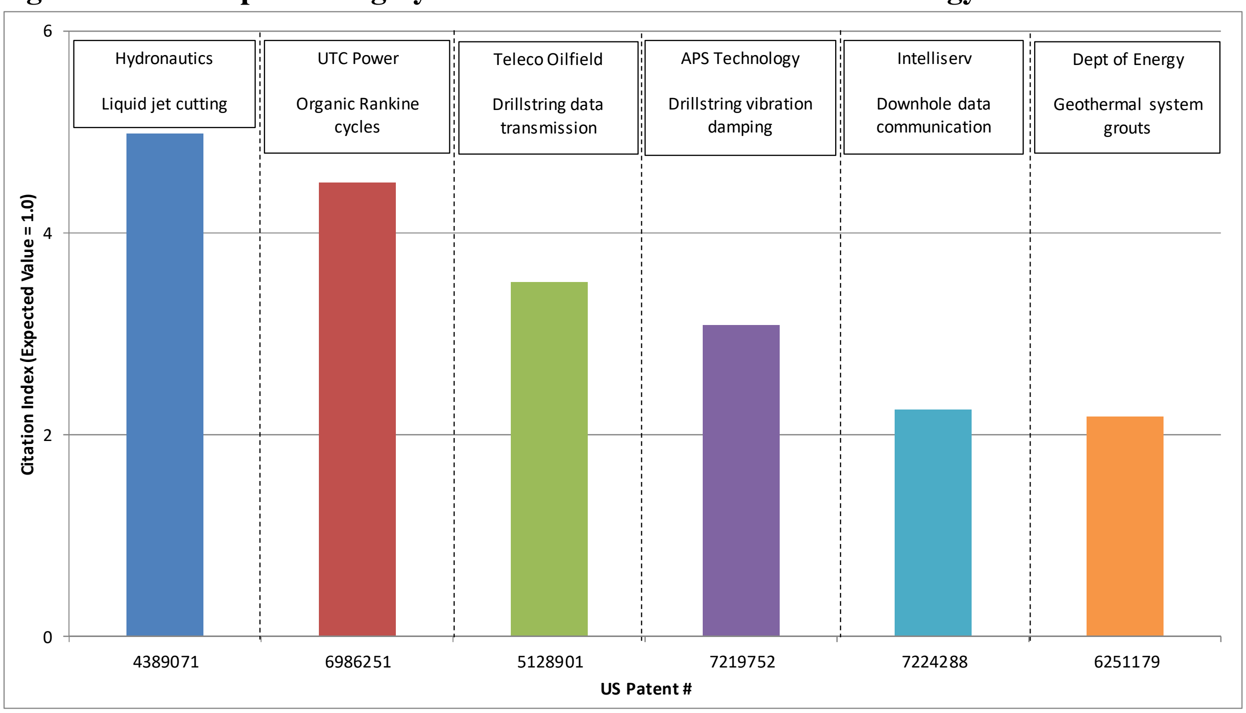
The simplest way of identifying high-impact GTO-funded geothermal energy patents is via overall Citation Indexes. The GTO-funded patents with the highest Citation Index values are shown in Table 9, with selected patents also presented in Figure 22. The patents in this table are a mix of older patents that have received large numbers of citations from subsequent generations of patents, and more recent patents that have attracted more citations than expected. One advantage of using Citation Indexes is that these two groups of patents can be compared directly, since each is benchmarked against peer patents of the same age and technology.

The patent at the head of Table 9 (US #4,389,071) is assigned to Hydronautics and describes a high velocity liquid jet that can be used in drilling applications. Since being issued in 2006, this patent has been cited as prior art by 73 subsequent patents, almost five times as many citations as expected given its age and technology. UTC Power has the patent in second place in Table 9 (US #6,986,251). This is one of three highly-cited UTC Power patents in this table related to organic Rankine cycles. It has been cited as prior art by 62 subsequent patents, more than four times as many citations as expected. The third-place patent in Table 9 (US #5,128,901) has been cited by 75 subsequent patents (more than three times as many as expected), making it the most highly-cited in the table in terms of raw citation counts. This patent is assigned to Teleco Oilfield Services, and outlines data transmission via a drill string.

Table 9 – List of Highly Cited GTO-Funded Geothermal Energy Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
4389071	1983	73	4.98	Hydronautics	Enhancing liquid jet erosion
6986251	2006	62	4.50	UTC Power	Organic Rankine cycle system for use with a reciprocating engine
5128901	1992	75	3.51	Teleco Oilfield Services	Acoustic data transmission through a drillstring
7174716	2007	36	3.11	UTC Power	Organic Rankine cycle waste heat applications
7219752	2007	49	3.09	APS Technology Inc	System and method for damping vibration in a drill string
6880344	2005	49	2.96	UTC Power	Combined Rankine and vapor compression cycles
7224288	2007	45	2.25	Intelliserv Inc	Link module for a downhole drilling network
6251179	2001	33	2.18	US Dept Energy	Thermally conductive cementitious grout for geothermal heat pump systems
4391339	1983	54	1.78	Hydronautics	Cavitating liquid jet assisted drill bit and method for deep hole drilling
4871395	1989	34	1.68	Associated Universities	High temperature lightweight foamed cements

Figure 22 – Examples of Highly-Cited GTO-funded Geothermal Energy Patents



The Citation Indexes in Table 9 are based on a single generation of citations to GTO-funded geothermal energy patents. Table 10 and Table 11 extend this by examining a second generation of citations – i.e. they show the GTO-funded geothermal energy patents linked directly or indirectly to the largest number of subsequent patent families.[13] These subsequent families are divided into two groups, based on whether they are within or beyond geothermal technology (i.e. whether or not they are in the universe of geothermal patents defined in the first stage of this project). This highlights which GTO-funded patent families have been particularly influential within geothermal technology, and which have had a wider impact beyond geothermal energy.

Table 10 – Pre-1995 GTO-funded Geothermal Energy Patent Families Linked via Citations to Largest Number of Subsequent Geothermal Energy/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Geotherm Fams	Assignee	Title
22804569	1980	4389071	903	2	Hydronautics	Enhancing liquid jet erosion
25460462	1978	4262757	734	3	Hydronautics	Cavitating liquid jet assisted drill bit and method for deep hole drilling
22149693	1993	5363095	487	4	Sandia Corp (SNL)	Downhole telemetry system
27497605	1988	5274606	480	3	AT&T	Circuit for echo and noise suppression of acoustic signals transmitted through a drill string
22264881	1987	4871395	470	2	Associated Universities	High temperature lightweight foamed cements
24422192	1988	5222049	305	2	Teleco Oilfield Services	Electromechanical transducer for acoustic telemetry system
23174648	1994	5477505	261	1	Sandia Corp (SNL)	Downhole pipe selection for acoustic telemetry
22585231	1980	4358930	252	20	US Dept Energy	Method of optimizing performance of Rankine cycle power plants
22572028	1980	4328106	239	35	US Dept Energy	Method for inhibiting silica precipitation and scaling in geothermal flow systems
22318495	1979	4326581	192	26	US Dept Energy	Direct contact, binary fluid geothermal boiler

Table 10 contains older patent families, with priority dates prior to 1995. The two patent families at the head of this table (representative patents US #4,389,632 and US #4,262,757) are both assigned to Hydronautics and describe high-velocity liquid jets. The first of these families contains the patent highlighted above with the highest Citation Index in Table 9. These two Hydronautics patent families are linked via citations to 903 and 734 subsequent patent families respectively, almost all of them from beyond geothermal technology. The third patent family in Table 10 is assigned to Sandia Corporation, through its management of Sandia National Laboratory (SNL). This family (representative patent #5,363,095) describes a downhole telemetry system, and is linked via citations to 487 subsequent patent families, again almost all from outside geothermal technology. Indeed, most of the patent families in Table 10 follow a similar citation pattern, with most citation links being from outside geothermal technology. That

[13] The GTO-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.

said, there are three patent families at the bottom of this table with more extensive citation links within geothermal technology. These families are all assigned to DOE, and describe geothermal power plants, scaling reduction in geothermal systems, and geothermal boilers.

Table 11 contains more recent GTO-funded geothermal energy patent families, with priority dates from 1995 onwards. That said, these families are all relatively old, dating from either side of the turn of this century. Patent families assigned to UTC Power for organic Rankine cycles feature prominently in Table 11, as they did in the list of highly-cited GTO-funded patents in Table 9. For example, the UTC patent family at the head of this table (representative patent US #6,880,344) is linked via citations to 244 subsequent families, almost all of them from outside geothermal technology. Sandia Corporation (SNL) also has a number of patent families in Table 11 related to acoustic transducers. These include the patent family in second place in this table (representative patent US #5,703,836), which is linked to 215 subsequent patent families, all of them from outside geothermal technology. Meanwhile, the patent family in third place in Table 11 is linked to 213 subsequent families, all of them again from outside geothermal technology. This family is assigned to APS Technology and describes a method for reducing vibrations in drill strings. Out of all the patent families in Table 11, only one has extensive citation links within geothermal technology. This patent family (representative patent US #6,251,179) is assigned to DOE and describes grouts for use in geothermal heat pumps. It is linked via citations to 144 subsequent families, 58 of which are within geothermal technology.

Table 11 – Post-1994 GTO-funded Geothermal Energy Patent Families Linked via Citations to Largest Number of Subsequent Geothermal Energy/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Geotherm Fams	Assignee	Title
46204872	2002	6880344	244	9	UTC Power	Combined Rankine and vapor compression cycles
24484394	1996	5703836	215	0	Sandia Corp (SNL)	Acoustic transducer
34590217	2003	7219752	213	0	APS Technology	System and method for damping vibration in a drill string
23188964	1999	6147932	177	0	Sandia Corp (SNL)	Acoustic transducer
33516988	2003	6986251	162	1	UTC Power	Organic Rankine cycle system for use with a reciprocating engine
25240917	1997	5925291	153	8	MRIGlobal (NREL)	Method and apparatus for high-efficiency direct contact condensation
23048583	1999	6251179	144	58	US Dept Energy	Thermally conductive cementitious grout for geothermal heat pump systems
23186326	1999	6188647	144	0	Sandia Corp (SNL)	Extension method of drillstring component assembly
22325272	1998	6182755	134	0	Sandia Corp (SNL)	Bellow seal and anchor
33552715	2003	7224288	91	0	Intelliserv	Link module for a downhole drilling network

The tables above identify GTO-funded patent families linked particularly strongly to subsequent technological developments. Table 12 looks in the opposite direction, and identifies highly-cited patents linked to earlier GTO-funded geothermal energy patents. As such, these are examples where GTO-funded geothermal energy research has formed part of the foundation for subsequent high-impact technologies. This table focuses on patents not owned by the leading geothermal energy companies, since those patents were examined in the backward tracing element of the analysis.

Table 12 - Highly Cited Patents (not from leading geothermal energy companies) Linked via Citations to Earlier GTO-funded Geothermal Energy Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
6670880	2003	246	18.15	Novatek Engineering	Downhole data transmission system
6969123	2005	295	17.73	Royal Dutch Shell	Upgrading and mining of coal
7524910	2009	114	12.14	ExxonMobil	Polyolefin adhesive compositions and articles made therefrom
6717501	2004	134	11.69	National Oilwell Varco	Downhole data transmission system
7832207	2010	94	10.58	General Compression	Systems and methods for energy storage and recovery using compressed gas
5868202	1999	385	8.29	Tarim Associates	Hydrologic cells for recovery of hydrocarbons or thermal energy from coal, oil-shale, tar-sands and oil-bearing formations
5938117	1999	148	7.62	Aerogen Inc	Methods and apparatus for dispensing liquids as an atomized spray
5746844	1998	74	7.25	Eaton Corp	Method and apparatus for creating a free-form three-dimensional article using a layer-by-layer deposition of molten metal
7410584	2008	50	6.66	Alfa-Laval AB	Methods and apparatus for treating wastewater employing a high rate clarifier and a membrane

The patent at the head of Table 12 (US #6,670,880) was granted in 2003 to Novatek Engineering. This patent describes data transmission in downhole applications. It has been cited as prior art by 246 subsequent patents, which is more than eighteen times as many citations as expected for a patent of its age and technology. The second patent in Table 12 (US #6,969,123) is assigned to Royal Dutch Shell and outlines a method for treating coal formations. This patent has been cited as prior art by 295 subsequent patents since it was issued in 2005, more than seventeen times as many citations as expected. In terms of raw citation counts, the most highly-cited patent in Table 12 was issued in 1999 and assigned to Tarim. This patent, which describes energy recovery from oil-shale and tar-sands, has been cited by 385 subsequent patents, more than eight times as many as expected. Table 12 also includes patents related to various other technologies, including adhesive compositions, energy storage, materials handling, and wastewater treatment. These examples reflect the breadth of influence of GTO-funded geothermal energy research on subsequent technological developments.

As with the backward tracing element of the analysis, the patent-level results from the forward tracing focus on GTO-funded geothermal energy patents. That said, within the forward tracing, we did also identify Other DOE-funded geothermal energy patent families linked to the largest number of subsequent patent families within and beyond geothermal technology. These Other DOE-funded geothermal energy families are shown in Table 13. Note that all but two of the patent families in this table (those assigned to Shell and Intelliserv) are marked as "unknown" in terms of their DOE funding source, rather than definitely not GTO-funded. Hence, they may in fact have been funded by GTO.

Table 13 - Other DOE-funded Geothermal Energy Patent Families Linked via Citations to Largest Number of Subsequent Geothermal Energy/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Geotherm Fams	Assignee	Title
39324928	2006	7540324	459	13	Royal Dutch Shell	Heating hydrocarbon containing formations in a checkerboard pattern staged process
25198037	1977	4106577	428	0	Univ Missouri	Hydromechanical drilling device
24853065	1991	5165243	408	6	US Dept Energy	Compact acoustic refrigerator
23605865	1982	4489563	396	49	Unassigned (Alexander Kalina)	Generation of energy
22897880	1972	3786858	367	136	US Dept Energy	Method of extracting heat from dry geothermal reservoirs
26757161	1987	4875015	330	1	Univ Utah	Multi-array borehole resistivity and induced polarization method
24359727	1996	5685362	285	57	Univ California (LANL)	Storage capacity in hot dry rock reservoirs
22415217	1999	6347675	195	4	Tempress Tech	Coiled tubing drilling with supercritical carbon dioxide
34138569	2003	7123160	175	0	Intelliserv	Method for triggering an action
21987191	1979	4556109	160	19	Dow Chemical	Process for cementing geothermal wells

The patent family at the head of Table 13 (representative patent US #7,540,324) is assigned to Royal Dutch Shell and describes a method for heating subsurface formations. This Shell patent family is linked via citations to 459 subsequent patent families, only 13 of which are related to geothermal energy, with many of the remainder being related to oilfield technologies. The second patent family in Table 13 (representative patent US #4,106,577) is assigned to the University of Missouri, and outlines a hydromechanical drilling device for cutting rocks. It is linked via citations to 428 subsequent families, all of which are outside geothermal technology. The third patent family in Table 13 (representative patent US #5,165,243) is also linked primarily to subsequent families beyond geothermal technology. This patent family is assigned to DOE, and describes a method for cooling electrical components in borehole applications. There are patent families in Table 13 with more extensive citation links to subsequent geothermal patents, notably the Kalina cycle patent family (highlighted earlier in Table 8) and a DOE patent family for extracting heat from dry geothermal reservoirs.

Overall, the forward tracing element of the analysis shows that GTO-funded and Other DOE-funded geothermal energy research has had a strong influence on subsequent technologies. This influence can be seen most extensively in geothermal and oilfield technologies, but can also be traced in other technologies such as energy storage, materials handling and wastewater treatment.

5.0 Conclusions

This report describes the results of an analysis tracing links between geothermal energy research funded by DOE (GTO plus Other DOE) and subsequent developments both within and beyond geothermal technology. This tracing is carried out both backwards and forwards in time. The purpose of the backward tracing is to determine the extent to which GTO-funded (and Other DOE-funded) research forms a foundation for innovations associated with the leading geothermal energy companies. The purpose of the forward tracing is to examine the influence of GTO-funded (and Other DOE-funded) geothermal energy patents upon subsequent developments, both within and outside geothermal technology.

The backward tracing element of the analysis suggests that the portfolios of GTO-funded and Other DOE-funded geothermal energy patents have had an important influence on subsequent innovations associated with the leading geothermal energy companies. This influence can be seen both over time and across technologies, with a various DOE-funded patent families linked via citations to subsequent patents assigned to a number of the leading companies. Meanwhile, the forward tracing element of the analysis shows that GTO-funded and Other DOE-funded geothermal energy research has had a strong influence on subsequent technologies. This influence can be seen most extensively within geothermal and oilfield technologies, but can also be traced in other technologies such as energy storage, materials handling and wastewater treatment.

Overall, the analysis presented in this report reveals that geothermal energy research funded by GTO, and by DOE in general, has had a significant influence on subsequent developments, both within and beyond geothermal technology. This influence can be seen on innovations associated with the leading geothermal energy companies, plus innovations across a range of other technologies.

Appendix A. GTO-funded Geothermal Energy Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Original Assignee	Title
4005289	1976	1977	US DEPARTMENT OF ENERGY	METHOD FOR IDENTIFYING ANOMALOUS TERRESTRIAL HEAT FLOWS
4262757	1978	1981	HYDRONAUTICS, INCORPORATED	CAVITATING LIQUID JET ASSISTED DRILL BIT AND METHOD FOR DEEP-HOLE DRILLING
EP0042752	1981	1981	US DEPARTMENT OF ENERGY	METHOD OF OPTIMIZING PERFORMANCE OF RANKINE CYCLE POWER PLANTS.
4326581	1979	1982	US DEPARTMENT OF ENERGY	DIRECT CONTACT, BINARY FLUID GEOTHERMAL BOILER
4328106	1980	1982	US DEPARTMENT OF ENERGY	METHOD FOR INHIBITING SILICA PRECIPITATION AND SCALING IN GEOTHERMAL FLOW SYSTEMS
4332520	1979	1982	US DEPARTMENT OF ENERGY	VELOCITY PUMP REACTION TURBINE
4346560	1980	1982	US DEPARTMENT OF ENERGY	MULTI-STAGE FLASH DEGASER
4358930	1980	1982	US DEPARTMENT OF ENERGY	METHOD OF OPTIMIZING PERFORMANCE OF RANKINE CYCLE POWER PLANTS
EP0062111	1981	1982	HYDRONAUTICS, INCORPORATED	ENHANCING LIQUID JET EROSION.
4389071	1980	1983	HYDRONAUTICS, INCORPORATED	ENHANCING LIQUID JET EROSION
4391339	1980	1983	HYDRONAUTICS, INCORPORATED	CAVITATING LIQUID JET ASSISTED DRILL BIT AND METHOD FOR DEEP-HOLE DRILLING
4430042	1982	1984	US DEPARTMENT OF ENERGY	VELOCITY PUMP REACTION TURBINE
4474251	1981	1984	HYDRONAUTICS, INCORPORATED	ENHANCING LIQUID JET EROSION
4681264	1984	1987	HYDRONAUTICS, INCORPORATED	ENHANCING LIQUID JET EROSION
4822422	1987	1989	ASSOCIATED UNIVERSITIES INC	CA(OH).SUB.2 -TREATED CERAMIC MICROSPHERE
4871395	1987	1989	ASSOCIATED UNIVERSITIES INC	HIGH TEMPERATURE LIGHTWEIGHT FOAMED CEMENTS
4927462	1988	1990	ASSOCIATED UNIVERSITIES INC	OXIDATION OF CARBON FIBER SURFACES FOR USE AS REINFORCEMENT IN HIGH-TEMPERATURE CEMENTITIOUS MATERIAL SYSTEMS
4936384	1988	1990	ASSOCIATED UNIVERSITIES INC	CA(OH).SUB.2 -TREATED CERAMIC MICROSPHERE
5056067	1990	1991	TELECO OILFIELD SERVICES INC	ANALOG CIRCUIT FOR CONTROLLING ACOUSTIC

				TRANSDUCER ARRAYS
5128901	1990	1992	TELECO OILFIELD SERVICES INC	ACOUSTIC DATA TRANSMISSION THROUGH A DRILLSTRING
5222049	1990	1993	TELECO OILFIELD SERVICES INC	ELECTROMECHANICAL TRANSDUCER FOR ACOUSTIC TELEMETRY SYSTEM
5246496	1992	1993	ASSOCIATED UNIVERSITIES INC	PHOSPHATE-BONDED CALCIUM ALUMINATE CEMENTS
5274606	1992	1993	UNASSIGNED	CIRCUIT FOR ECHO AND NOISE SUPPRESSION OF ACCOUSTIC SIGNALS TRANSMITTED THROUGH A DRILL STRING
5343968	1991	1994	US DEPARTMENT OF ENERGY	DOWNHOLE MATERIAL INJECTOR FOR LOST CIRCULATION CONTROL
5363095	1993	1994	SANDIA CORP	DOWNHOLE TELEMETRY SYSTEM
5366891	1993	1994	ASSOCIATED UNIVERSITIES INC	BIOCHEMICAL SOLUBILIZATION OF TOXIC SALTS FROM RESIDUAL GEOTHERMAL BRINES AND WASTE WATERS
5477505	1994	1995	SANDIA CORP	DOWNHOLE PIPE SELECTION FOR ACOUSTIC TELEMETRY
5567932	1995	1996	SANDIA CORP	GEOMEMBRANE BARRIERS USING INTEGRAL FIBER OPTICS TO MONITOR BARRIER INTEGRITY
5703836	1996	1997	SANDIA CORP	ACOUSTIC TRANSDUCER
WO1997039219	1997	1997	SANDIA CORP	APPARATUS AND METHOD FOR DOWNHOLE DRILLING COMMUNICATIONS
5722488	1996	1998	SANDIA CORP	APPARATUS FOR DOWNHOLE DRILLING COMMUNICATIONS AND METHOD FOR MAKING AND USING THE SAME
5823261	1996	1998	SANDIA CORP	WELL-PUMP ALIGNMENT SYSTEM
WO1998042434	1997	1998	MIDWEST RESEARCH INSTITUTE	METHOD AND APPARATUS FOR HIGH-EFFICIENCY DIRECT CONTACT CONDENSATION
5925291	1997	1999	MIDWEST RESEARCH INSTITUTE	METHOD AND APPARATUS FOR HIGH-EFFICIENCY DIRECT CONTACT CONDENSATION
EP0900317	1997	1999	SANDIA CORP	APPARATUS AND METHOD FOR DOWNHOLE DRILLING COMMUNICATIONS
6147932	1999	2000	SANDIA CORP	ACOUSTIC TRANSDUCER
6182755	1998	2001	SANDIA CORP	BELLOW SEAL AND ANCHOR
6188647	1999	2001	SANDIA CORP	EXTENSION METHOD OF DRILLSTRING COMPONENT

				ASSEMBLY
6251179	1999	2001	US DEPARTMENT OF ENERGY	THERMALLY CONDUCTIVE CEMENTITIOUS GROUT FOR GEOTHERMAL HEAT PUMP SYSTEMS
6282497	1999	2001	MIDWEST RESEARCH INSTITUTE	METHOD FOR ANALYZING THE CHEMICAL COMPOSITION OF LIQUID EFFLUENT FROM A DIRECT CONTACT CONDENSER
6427791	2001	2002	US DEPARTMENT OF ENERGY	DRILL BIT ASSEMBLY FOR RELEASABLY RETAINING A DRILL BIT CUTTER
6791470	2001	2004	SANDIA CORP	REDUCING INJECTION LOSS IN DRILL STRINGS
WO2004043606	2003	2004	UTC POWER LLC	ORGANIC RANKINE CYCLE WASTE HEAT APPLICATIONS
6853798	2002	2005	SANDIA CORP	DOWNHOLE GEOTHERMAL WELL SENSORS COMPRISING A HYDROGEN-RESISTANT OPTICAL FIBER
6880344	2003	2005	UTC POWER LLC	COMBINED RANKINE AND VAPOR COMPRESSION CYCLES
EP1567750	2003	2005	UTC POWER LLC	ORGANIC RANKINE CYCLE SYSTEM AND OPERATING METHOD
WO2005047640	2004	2005	APS TECHNOLOGY INC	SYTEM AND METHOD FOR DAMPING VIBRATION IN A DRILL STRING
WO2005078046	2005	2005	UNITED TECHNOLOGIES CORP	ORGANIC RANKINE CYCLE FLUID
6986251	2003	2006	UTC POWER LLC	ORGANIC RANKINE CYCLE SYSTEM FOR USE WITH A RECIPROCATING ENGINE
7036612	2003	2006	SANDIA CORP	CONTROLLABLE MAGNETO-RHEOLOGICAL FLUID-BASED DAMPERS FOR DRILLING
7100380	2004	2006	UNITED TECHNOLOGIES CORP	ORGANIC RANKINE CYCLE FLUID
EP1713877	2005	2006	UNITED TECHNOLOGIES CORP	ORGANIC RANKINE CYCLE FLUID
7174716	2002	2007	UTC POWER LLC	ORGANIC RANKINE CYCLE WASTE HEAT APPLICATIONS
7219752	2004	2007	APS TECHNOLOGY INC	SYSTEM AND METHOD FOR DAMPING VIBRATION IN A DRILL STRING
7224288	2003	2007	INTELLISERV INC	LINK MODULE FOR A DOWNHOLE DRILLING NETWORK
7377339	2007	2008	APS TECHNOLOGY INC	SYSTEM AND METHOD FOR DAMPING VIBRATION IN A DRILL STRING

WO2009079047	2008	2009	L. LIVERMORE NATIONAL SECURITY LLC	SILICA EXTRACTION FROM GEOTHERMAL WATER
WO2009117354	2009	2009	ELTRON RESEARCH & DEVELOPMENT INC	ELECTROWINNING APPARATUS AND PROCESS
WO2010101902	2010	2010	APS TECHNOLOGY INC	SYSTEM AND METHOD FOR DAMPING VIBRATION IN A DRILL STRING USING A MAGNETORHEOLOGICAL DAMPER
7997357	2008	2011	APS TECHNOLOGY INC	SYSTEM AND METHOD FOR DAMPING VIBRATION IN A DRILL STRING
WO2011103298	2011	2011	SIMBOL INC	PROCESSES FOR PREPARING HIGHLY PURE LITHIUM CARBONATE AND OTHER HIGHLY PURE LITHIUM CONTAINING COMPOUNDS
8087476	2009	2012	APS TECHNOLOGY INC	SYSTEM AND METHOD FOR DAMPING VIBRATION IN A DRILL STRING USING A MAGNETORHEOLOGICAL DAMPER
8202411	2008	2012	ELTRON RESEARCH & DEVELOPMENT INC	ELECTROWINNING APPARATUS AND PROCESS
8240401	2011	2012	APS TECHNOLOGY INC	SYSTEM AND METHOD FOR DAMPING VIBRATION IN A DRILL STRING
8287829	2011	2012	SIMBOL INC	PROCESSES FOR PREPARING HIGHLY PURE LITHIUM CARBONATE AND OTHER HIGHLY PURE LITHIUM CONTAINING COMPOUNDS
EP2404076	2010	2012	APS TECHNOLOGY INC	SYSTEM AND METHOD FOR DAMPING VIBRATION IN A DRILL STRING USING A MAGNETORHEOLOGICAL DAMPER
EP2536663	2011	2012	SIMBOL INC	PROCESS FOR PREPARING HIGHLY PURE LITHIUM CARBONATE
8430166	2010	2013	UNIVERSITY OF NEVADA	GEOTHERMAL ENERGY EXTRACTION SYSTEM AND METHOD
8435468	2011	2013	SIMBOL INC	PROCESSES FOR PREPARING HIGHLY PURE LITHIUM CARBONATE AND OTHER HIGHLY PURE LITHIUM CONTAINING COMPOUNDS
8454816	2010	2013	SIMBOL INC	SELECTIVE RECOVERY OF MANGANESE AND ZINC FROM GEOTHERMAL BRINES

8518232	2012	2013	SIMBOL INC	SELECTIVE RECOVERY OF MANGANESE, LEAD AND ZINC
8574519	2011	2013	SIMBOL INC	PROCESSES FOR PREPARING HIGHLY PURE LITHIUM CARBONATE AND OTHER HIGHLY PURE LITHIUM CONTAINING COMPOUNDS
8597521	2010	2013	SIMBOL INC	SELECTIVE REMOVAL OF SILICA FROM SILICA CONTAINING BRINES
WO2013036796	2012	2013	APS TECHNOLOGY INC	SYSTEM AND METHOD FOR DAMPING VIBRATION IN A DRILL STRING USING A MAGNETORHEOLOGICAL DAMPER
8637428	2010	2014	SIMBOL INC	LITHIUM EXTRACTION COMPOSITION AND METHOD OF PREPARATION THEREOF
8662205	2012	2014	APS TECHNOLOGY INC	SYSTEM AND METHOD FOR DAMPING VIBRATION IN A DRILL STRING
8741256	2010	2014	SIMBOL INC	PREPARATION OF LITHIUM CARBONATE FROM LITHIUM CHLORIDE CONTAINING BRINES
8753594	2010	2014	SIMBOL INC	SORBENT FOR LITHIUM EXTRACTION
8840859	2008	2014	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	SILICA EXTRACTION FROM GEOTHERMAL WATER
8901032	2011	2014	SIMBOL INC	POROUS ACTIVATED ALUMINA BASED SORBENT FOR LITHIUM EXTRACTION
EP2749535	2011	2014	SIMBOL INC	PROCESSES FOR PREPARING HIGHLY PURE LITHIUM CARBONATE AND OTHER HIGHLY PURE LITHIUM CONTAINING COMPOUNDS
WO2014003871	2013	2014	GENERAL ELECTRIC CO	ELECTRIC MACHINE AND SYSTEMS COMPRISING THE SAME
WO2014004092	2013	2014	L. LIVERMORE NATIONAL SECURITY LLC	HIGH STRAIN RATE METHOD OF PRODUCING OPTIMIZED FRACTURE NETWORKS IN RESERVOIRS
8944190	2014	2015	APS TECHNOLOGY INC	SYSTEM AND METHOD FOR DAMPING VIBRATION IN A DRILL STRING
9012357	2013	2015	SIMBOL INC	LITHIUM EXTRACTION COMPOSITION AND METHOD OF PREPARATION THEREOF
9034295	2014	2015	SIMBOL INC	PREPARATION OF LITHIUM CARBONATE FROM LITHIUM CHLORIDE CONTAINING

				BRINES
9051827	2010	2015	SIMBOL INC	SELECTIVE REMOVAL OF SILICA FROM SILICA CONTAINING BRINES
9057117	2013	2015	SIMBOL INC	SELECTIVE RECOVERY OF MANGANESE AND ZINC FROM GEOTHERMAL BRINES
9062545	2012	2015	L. LIVERMORE NATIONAL SECURITY LLC	HIGH STRAIN RATE METHOD OF PRODUCING OPTIMIZED FRACTURE NETWORKS IN RESERVOIRS
9074265	2013	2015	SIMBOL INC	PROCESSES FOR PREPARING HIGHLY PURE LITHIUM CARBONATE AND OTHER HIGHLY PURE LITHIUM CONTAINING COMPOUNDS
9145865	2012	2015	GENERAL ELECTRIC CO	ELECTRIC FLUID PUMP
9209766	2013	2015	SANDIA CORP	HIGH TEMPERATURE CHARGE AMPLIFIER FOR GEOTHERMAL APPLICATIONS
9222149	2014	2015	SIMBOL INC	PREPARATION OF LITHIUM CARBONATE FROM LITHIUM CHLORIDE CONTAINING BRINES
WO2015195847	2015	2015	L. LIVERMORE NATIONAL SECURITY LLC	MULTI-FLUID RENEWABLE GEO-ENERGY SYSTEMS AND METHODS
9238851	2013	2016	SIMBOL INC	SELECTIVE RECOVERY OF MANGANESE, LEAD AND ZINC
9249478	2013	2016	SIMBOL INC	SELECTIVE RECOVERY OF MANGANESE, LEAD AND ZINC
9279321	2013	2016	L. LIVERMORE NATIONAL SECURITY LLC	ENCAPSULATED MICROSENSORS FOR RESERVOIR INTERROGATION
9447315	2014	2016	BATTELLE MEMORIAL INSTITUTE	ELECTROPHILIC ACID GAS-REACTIVE FLUID, PROPPANT, AND PROCESS FOR ENHANCED FRACTURING AND RECOVERY OF ENERGY PRODUCING MATERIALS
9500068	2014	2016	UT-BATTELLE LLC	CAVITATION-BASED HYDRO-FRACTURING SIMULATOR
9527753	2013	2016	GEOTHERMAL ENERGY PROJECT LLC	PRODUCTION OF ZINC CHLORIDE AND ZINC SULFATE FROM GEOTHERMAL BRINES
9534276	2012	2017	GEOTHERMAL ENERGY PROJECT LLC	SEPARATION OF MANGANESE FROM BRINE
9574431	2014	2017	UT-BATTELLE LLC	CAVITATION-BASED HYDRO-FRACTURING TECHNIQUE FOR GEOTHERMAL RESERVOIR STIMULATION

9644126	2014	2017	SIMBOL INC	TREATED GEOTHERMAL BRINE COMPOSITIONS WITH REDUCED CONCENTRATIONS OF SILICA, IRON, AND ZINC
9644866	2014	2017	SIMBOL INC	TREATED BRINE COMPOSITIONS WITH REDUCED CONCENTRATIONS OF POTASSIUM, RUBIDIUM, AND CESIUM
9650555	2014	2017	SIMBOL INC	TREATED GEOTHERMAL BRINE COMPOSITIONS WITH REDUCED CONCENTRATIONS OF IRON AND SILICA
9739509	2014	2017	L. LIVERMORE NATIONAL SECURITY LLC	MULTI-FLUID RENEWABLE GEO-ENERGY SYSTEMS AND METHODS
9764318	2014	2017	ALGER ALTERNATIVE ENERGY LLC	POROUS ACTIVATED ALUMINA BASED SORBENT FOR LITHIUM EXTRACTION
9765604	2014	2017	L. LIVERMORE NATIONAL SECURITY LLC	SYSTEMS AND METHODS FOR MULTI-FLUID GEOTHERMAL ENERGY SYSTEMS
WO2017048329	2016	2017	SOUTHERN RESEARCH INSTITUTE	THERMOELECTRIC POWER GENERATION AND MINERAL EXTRACTION FROM BRINES
9863243	2015	2018	SANDIA CORP	RUGGEDIZED DOWNHOLE TOOL FOR REAL-TIME MEASUREMENTS AND USES THEREOF
9873828	2016	2018	BATTELLE MEMORIAL INSTITUTE	ELECTROPHILIC ACID GAS-REACTIVE FLUID, PROPPANT, AND PROCESS FOR ENHANCED FRACTURING AND RECOVERY OF ENERGY PRODUCING MATERIALS
9909052	2012	2018	L. LIVERMORE NATIONAL SECURITY LLC	USING COLLOIDAL SILICA AS ISOLATOR, DIVERTER AND BLOCKING AGENT FOR SUBSURFACE GEOLOGICAL APPLICATIONS
9976360	2011	2018	APS TECHNOLOGY INC	SYSTEM AND METHOD FOR DAMPING VIBRATION IN A DRILL STRING USING A MAGNETORHEOLOGICAL DAMPER
9995121	2014	2018	SIMBOL INC	SELECTIVE REMOVAL OF SILICA FROM SILICA CONTAINING BRINES
10024296	2015	2018	GENERAL ELECTRIC CO	ELECTRIC MACHINE INCLUDING A STATOR DEFINING A FLOW CHANNEL
10038131	2016	2018	SOUTHERN RESEARCH INSTITUTE	THERMOELECTRIC POWER GENERATION AND MINERAL EXTRACTION FROM BRINES
10328424	2017	2019	ALL AMERICAN LITHIUM LLC	POROUS ACTIVATED ALUMINA BASED SORBENT

				FOR LITHIUM EXTRACTION
10538990	2018	2020	L. LIVERMORE NATIONAL SECURITY LLC	USING COLLOIDAL SILICA AS A ZONAL ISOLATION MATERIAL AND FAST PATH BLOCKER IN GEOLOGICAL FORMATIONS
EP3594382	2011	2020	SIMBOL INC	PROCESSES FOR PREPARING HIGHLY PURE LITHIUM CARBONATE

Appendix B. Other DOE-Funded Geothermal Energy Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Original Assignee	Title
3938334	1974	1976	UNISYS CORP	GEOTHERMAL ENERGY CONTROL SYSTEM AND METHOD
4025240	1975	1977	UNISYS CORP	GEOTHERMAL ENERGY CONTROL SYSTEM AND METHOD
4078904	1976	1978	US DEPARTMENT OF ENERGY	PROCESS FOR FORMING HYDROGEN AND OTHER FUELS UTILIZING MAGMA
4106577	1977	1978	UNIVERSITY OF MISSOURI	HYDROMECHANICAL DRILLING DEVICE
4119160	1977	1978	UNIVERSITY OF MISSOURI	METHOD AND APPARATUS FOR WATER JET DRILLING OF ROCK
4134077	1977	1979	SYSTEM DEVELOPMENT CORP	AMPLIFIER CIRCUIT OPERABLE OVER A WIDE TEMPERATURE RANGE
4167099	1978	1979	OCCIDENTAL PETROLEUM CORP	COUNTERCURRENT DIRECT CONTACT HEAT EXCHANGE PROCESS AND SYSTEM
WO1979000565	1979	1979	OCCIDENTAL PETROLEUM CORP	COUNTERCURRENT DIRECT CONTACT HEAT EXCHANGE PROCESS AND SYSTEM
4196183	1979	1980	US DEPARTMENT OF ENERGY	PROCESS FOR PURIFYING GEOTHERMAL STEAM
4265487	1979	1981	UNIVERSITY OF MISSOURI	HIGH PRESSURE WATER JET MINING MACHINE
4276748	1979	1981	OCCIDENTAL PETROLEUM CORP	RECOVERY OF ENERGY FROM GEOTHERMAL BRINE AND OTHER HOT WATER SOURCES
4306879	1979	1981	US DEPARTMENT OF ENERGY	CHEMICAL LOGGING OF GEOTHERMAL WELLS
4313342	1980	1982	US DEPARTMENT OF ENERGY	METHOD AND APPARATUS FOR DETERMINING VERTICAL HEAT FLUX OF GEOTHERMAL FIELD
4317492	1980	1982	UNIVERSITY OF MISSOURI	METHOD AND APPARATUS FOR DRILLING HORIZONTAL HOLES IN GEOLOGICAL STRUCTURES FROM A VERTICAL BORE
4342197	1980	1982	UNISYS CORP	GEOTHERMAL PUMP DOWN-HOLE ENERGY REGENERATION SYSTEM
4376462	1981	1983	US DEPARTMENT OF ENERGY	SUBSTANTIALLY SELF-POWERED METHOD AND APPARATUS FOR RECOVERING HYDROCARBONS FROM HYDROCARBON-CONTAINING SOLID HYDRATES
4380903	1981	1983	UNISYS CORP	ENTHALPY RESTORATION IN

				GEOTHERMAL ENERGY PROCESSING SYSTEM
4424858	1982	1984	US DEPARTMENT OF ENERGY	APPARATUS FOR RECOVERING GASEOUS HYDROCARBONS FROM HYDROCARBON-CONTAINING SOLID HYDRATES
4489563	1982	1984	UNASSIGNED	GENERATION OF ENERGY
EP0101244	1983	1984	UNASSIGNED	GENERATION OF ENERGY.
4513352	1984	1985	US DEPARTMENT OF ENERGY	THERMAL PROTECTION APPARATUS
4556109	1979	1985	DOW CHEMICAL CO	PROCESS FOR CEMENTING GEOTHERMAL WELLS
4559818	1984	1985	US DEPARTMENT OF ENERGY	THERMAL WELL-TEST METHOD
4741398	1986	1988	US DEPARTMENT OF ENERGY	HYDRAULIC ACCUMULATOR-COMPRESSOR FOR GEOPRESSURED ENHANCED OIL RECOVERY
4824447	1986	1989	US DEPARTMENT OF ENERGY	ENHANCED OIL RECOVERY SYSTEM
4875015	1988	1989	UNIVERSITY OF UTAH	MULTI-ARRAY BOREHOLE RESISTIVITY AND INDUCED POLARIZATION METHOD WITH MATHEMATICAL INVERSION OF REDUNDANT DATA
WO1989000705	1988	1989	UNIVERSITY OF UTAH	MULTI-ARRAY BOREHOLE RESISTIVITY AND INDUCED POLARIZATION SYSTEM
5121993	1990	1992	US DEPARTMENT OF ENERGY	TRIAXIAL THERMOPILE ARRAY GEO-HEAT-FLOW SENSOR
5165243	1991	1992	US DEPARTMENT OF ENERGY	COMPACT ACOUSTIC REFRIGERATOR
5311766	1992	1994	US DEPARTMENT OF ENERGY	METHOD AND APPARATUS FOR DETERMINING TWO-PHASE FLOW IN ROCK FRACTURE
5604040	1995	1997	ASSOCIATED UNIVERSITIES INC	ZINC PHOSPHATE CONVERSION COATINGS
5685362	1996	1997	UNIVERSITY OF CALIFORNIA	STORAGE CAPACITY IN HOT DRY ROCK RESERVOIRS
6347675	2000	2002	TEMPRESS TECHNOLOGIES INC	COILED TUBING DRILLING WITH SUPERCRITICAL CARBON DIOXIDE
6537796	1999	2003	BROOKHAVEN SCIENCE ASSOCIATES LLC	CONVERSION OF GEOTHERMAL WASTE TO COMMERCIAL PRODUCTS INCLUDING SILICA
6668554	1999	2003	UNIVERSITY OF CALIFORNIA	GEOTHERMAL ENERGY PRODUCTION WITH SUPERCRITICAL FLUIDS
WO2005031106	2004	2005	INTELLISERV INC	LOAD-RESISTANT COAXIAL TRANSMISSION LINE
WO2005052303	2004	2005	INTELLISERV	DISTRIBUTED DOWNHOLE

			INC	DRILLING NETWORK
WO2005079224	2005	2005	TEMPRESS TECHNOLOGIES INC	HYDRAULIC IMPULSE GENERATOR AND FREQUENCY SWEEP MECHANISM FOR BOREHOLE APPLICATIONS
6982384	2003	2006	INTELLISERV INC	LOAD-RESISTANT COAXIAL TRANSMISSION LINE
7098802	2002	2006	INTELLISERV INC	SIGNAL CONNECTION FOR A DOWNHOLE TOOL STRING
7123160	2004	2006	INTELLISERV INC	METHOD FOR TRIGGERING AN ACTION
7139218	2004	2006	INTELLISERV INC	DISTRIBUTED DOWNHOLE DRILLING NETWORK
7139219	2004	2006	TEMPRESS TECHNOLOGIES INC	HYDRAULIC IMPULSE GENERATOR AND FREQUENCY SWEEP MECHANISM FOR BOREHOLE APPLICATIONS
7142129	2004	2006	INTELLISERV INC	METHOD AND SYSTEM FOR DOWNHOLE CLOCK SYNCHRONIZATION
EP1664475	2004	2006	INTELLISERV INC	LOAD-RESISTANT COAXIAL TRANSMISSION LINE
EP1718995	2004	2006	INTELLISERV INC	DISTRIBUTED DOWNHOLE DRILLING NETWORK
WO2006119022	2006	2006	APS TECHNOLOGY INC	ROTARY STEERABLE MOTOR SYSTEM FOR UNDERGROUND DRILLING
WO2006119294	2006	2006	APS TECHNOLOGY INC	METHODS AND SYSTEMS FOR DETERMINING ANGULAR ORIENTATION OF A DRILL STRING
7193526	2005	2007	INTELLISERV INC	DOWNHOLE TOOL
7193527	2004	2007	INTELLISERV INC	SWIVEL ASSEMBLY
7200070	2004	2007	INTELLISERV INC	DOWNHOLE DRILLING NETWORK USING BURST MODULATION TECHNIQUES
7207396	2004	2007	INTELLISERV INC	METHOD AND APPARATUS OF ASSESSING DOWN-HOLE DRILLING CONDITIONS
WO2007001344	2005	2007	UCHICAGO ARGONNE LLC	CHEMICALLY BONDED PHOSPHATE CERAMIC SEALANT FORMULATIONS FOR OIL FIELD APPLICATIONS
WO2007102863	2006	2007	HONEYWELL INTERNATIONAL INC	PING-PONG AUTO-ZERO AMPLIFIER WITH GLITCH REDUCTION
7321260	2006	2008	HONEYWELL INTERNATIONAL INC	PING-PONG AUTO-ZERO AMPLIFIER WITH GLITCH REDUCTION
7389830	2005	2008	APS TECHNOLOGY INC	ROTARY STEERABLE MOTOR SYSTEM FOR UNDERGROUND DRILLING
7438755	2005	2008	UCHICAGO ARGONNE LLC	CHEMICALLY BONDED PHOSPHATE CERAMIC

				SEALANT FORMULATIONS FOR OIL FIELD APPLICATIONS
EP1992067	2006	2008	HONEYWELL INTERNATIONAL INC	PING-PONG AUTO-ZERO AMPLIFIER WITH GLITCH REDUCTION
WO2008051495	2007	2008	SHELL OIL CO	SYSTEMS AND PROCESSES FOR USE IN TREATING SUBSURFACE FORMATIONS
WO2008051822	2007	2008	SHELL OIL CO	HEATING TAR SANDS FORMATIONS TO VISBREAKING TEMPERATURES
WO2008051825	2007	2008	SHELL OIL CO	WAX BARRIER FOR USE WITH IN SITU PROCESSES FOR TREATING FORMATIONS
WO2008051827	2007	2008	SHELL OIL CO	HEATING TAR SANDS FORMATIONS WHILE CONTROLLING PRESSURE
WO2008051830	2007	2008	SHELL OIL CO	MOVING HYDROCARBONS THROUGH PORTIONS OF TAR SANDS FORMATIONS WITH A FLUID
WO2008051831	2007	2008	SHELL OIL CO	HEATING HYDROCARBON CONTAINING FORMATIONS IN A LINE DRIVE STAGED PROCESS
WO2008051833	2007	2008	SHELL OIL CO	HEATING HYDROCARBON CONTAINING FORMATIONS IN A CHECKERBOARD PATTERN STAGED PROCESS
WO2008051834	2007	2008	SHELL OIL CO	HEATING HYDROCARBON CONTAINING FORMATIONS IN A SPIRAL STARTUP STAGED SEQUENCE
WO2008051836	2007	2008	SHELL OIL CO	IN SITU HEAT TREATMENT PROCESS UTILIZING A CLOSED LOOP HEATING SYSTEM
WO2008051837	2007	2008	SHELL OIL CO	IN SITU HEAT TREATMENT PROCESS UTILIZING OXIDIZERS TO HEAT A SUBSURFACE FORMATION
7540324	2007	2009	SHELL OIL CO	HEATING HYDROCARBON CONTAINING FORMATIONS IN A CHECKERBOARD PATTERN STAGED PROCESS
7562707	2007	2009	SHELL OIL CO	HEATING HYDROCARBON CONTAINING FORMATIONS IN A LINE DRIVE STAGED PROCESS
7586934	2004	2009	INTELLISERV INC	APPARATUS FOR FIXING LATENCY
7631690	2007	2009	SHELL OIL CO	HEATING HYDROCARBON CONTAINING FORMATIONS IN A SPIRAL STARTUP STAGED SEQUENCE
7635024	2007	2009	SHELL OIL CO	HEATING TAR SANDS

				FORMATIONS TO VISBREAKING TEMPERATURES
EP2074279	2007	2009	SHELL OIL CO	MOVING HYDROCARBONS THROUGH PORTIONS OF TAR SANDS FORMATIONS WITH A FLUID
EP2074281	2007	2009	SHELL OIL CO	HEATING TAR SANDS FORMATIONS WHILE CONTROLLING PRESSURE
EP2074282	2007	2009	SHELL OIL CO	IN SITU HEAT TREATMENT PROCESS UTILIZING A CLOSED LOOP HEATING SYSTEM
EP2074283	2007	2009	SHELL OIL CO	HEATING TAR SANDS FORMATIONS TO VISBREAKING TEMPERATURES
EP2074284	2007	2009	SHELL OIL CO	HEATING HYDROCARBON CONTAINING FORMATIONS IN A LINE DRIVE STAGED PROCESS
7644765	2007	2010	SHELL OIL CO	HEATING TAR SANDS FORMATIONS WHILE CONTROLLING PRESSURE
7673681	2007	2010	SHELL OIL CO	TREATING TAR SANDS FORMATIONS WITH KARSTED ZONES
7677310	2007	2010	SHELL OIL CO	CREATING AND MAINTAINING A GAS CAP IN TAR SANDS FORMATIONS
7677314	2007	2010	SHELL OIL CO	METHOD OF CONDENSING VAPORIZED WATER IN SITU TO TREAT TAR SANDS FORMATIONS
7681647	2007	2010	SHELL OIL CO	METHOD OF PRODUCING DRIVE FLUID IN SITU IN TAR SANDS FORMATIONS
7681663	2006	2010	APS TECHNOLOGY INC	METHODS AND SYSTEMS FOR DETERMINING ANGULAR ORIENTATION OF A DRILL STRING
7703513	2007	2010	SHELL OIL CO	WAX BARRIER FOR USE WITH IN SITU PROCESSES FOR TREATING FORMATIONS
7717171	2007	2010	SHELL OIL CO	MOVING HYDROCARBONS THROUGH PORTIONS OF TAR SANDS FORMATIONS WITH A FLUID
7730945	2007	2010	SHELL OIL CO	USING GEOTHERMAL ENERGY TO HEAT A PORTION OF A FORMATION FOR AN IN SITU HEAT TREATMENT PROCESS
7730946	2007	2010	SHELL OIL CO	TREATING TAR SANDS FORMATIONS WITH DOLOMITE
7730947	2007	2010	SHELL OIL CO	CREATING FLUID INJECTIVITY

				IN TAR SANDS FORMATIONS
7762356	2008	2010	APS TECHNOLOGY INC	ROTARY STEERABLE MOTOR SYSTEM FOR UNDERGROUND DRILLING
7841401	2007	2010	SHELL OIL CO	GAS INJECTION TO INHIBIT MIGRATION DURING AN IN SITU HEAT TREATMENT PROCESS
7845411	2007	2010	SHELL OIL CO	IN SITU HEAT TREATMENT PROCESS UTILIZING A CLOSED LOOP HEATING SYSTEM
WO2010074980	2009	2010	UNASSIGNED	METHOD AND APPARATUS FOR INCREASING WELL PRODUCTIVITY
8191630	2010	2012	SHELL OIL CO	CREATING FLUID INJECTIVITY IN TAR SANDS FORMATIONS
8555971	2012	2013	SHELL OIL CO	TREATING TAR SANDS FORMATIONS WITH DOLOMITE
WO2013009895	2012	2013	L. LIVERMORE NATIONAL SECURITY LLC	ENCAPSULATED TRACERS AND CHEMICALS FOR RESERVOIR INTERROGATION AND MANIPULATION
WO2013059497	2012	2013	LOS ALAMOS NATIONAL SECURITY LLC	COOLING DEVICES AND METHODS FOR USE WITH ELECTRIC SUBMERSIBLE PUMPS
8663361	2011	2014	SANDIA CORP	METHODS OF RECOVERING ALKALI METALS
8877506	2012	2014	L. LIVERMORE NATIONAL SECURITY LLC	METHODS AND SYSTEMS USING ENCAPSULATED TRACERS AND CHEMICALS FOR RESERVOIR INTERROGATION AND MANIPULATION
8899054	2012	2014	LOS ALAMOS NATIONAL SECURITY LLC	COOLING DEVICES AND METHODS FOR USE WITH ELECTRIC SUBMERSIBLE PUMPS
EP2769099	2012	2014	LOS ALAMOS NATIONAL SECURITY LLC	COOLING DEVICES AND METHODS FOR USE WITH ELECTRIC SUBMERSIBLE PUMPS
WO2014036300	2013	2014	CHEVRON USA INC, L. LIVERMORE NATIONAL SECURITY LLC	SYSTEM AND METHOD FOR DETERMINING A PROBABILITY OF WELL SUCCESS USING STOCHASTIC INVERSION
WO2014036306	2013	2014	CHEVRON USA INC, L. LIVERMORE NATIONAL SECURITY LLC	SYSTEM AND METHOD FOR DETERMINING A VALUE OF INFORMATION METRIC FROM A POSTERIOR DISTRIBUTION GENERATED THROUGH STOCHASTIC INVERSION
WO2014107608	2014	2014	CARBO CERAMICS INC,	ELECTRICALLY CONDUCTIVE PROPPANT AND METHODS

			SANDIA CORP	FOR DETECTING, LOCATING AND CHARACTERIZING THE ELECTRICALLY CONDUCTIVE PROPPANT
WO2014159265	2014	2014	L. LIVERMORE NATIONAL SECURITY LLC	ENCAPSULATED PROPPANTS
8931553	2014	2015	CARBO CERAMICS INC, SANDIA CORP	ELECTRICALLY CONDUCTIVE PROPPANT AND METHODS FOR DETECTING, LOCATING AND CHARACTERIZING THE ELECTRICALLY CONDUCTIVE PROPPANT
9002766	2012	2015	CHEVRON USA INC, L. LIVERMORE NATIONAL SECURITY LLC	SYSTEM AND METHOD FOR DETERMINING A VALUE OF INFORMATION METRIC FROM A POSTERIOR DISTRIBUTION GENERATED THROUGH STOCHASTIC INVERSION
9183182	2012	2015	CHEVRON USA INC, L. LIVERMORE NATIONAL SECURITY LLC	SYSTEM AND METHOD FOR DETERMINING A PROBABILITY OF WELL SUCCESS USING STOCHASTIC INVERSION
EP2890999	2013	2015	CHEVRON USA INC, L. LIVERMORE NATIONAL SECURITY LLC	SYSTEM AND METHOD FOR DETERMINING A VALUE OF INFORMATION METRIC FROM A POSTERIOR DISTRIBUTION GENERATED THROUGH STOCHASTIC INVERSION
EP2891114	2013	2015	CHEVRON USA INC, L. LIVERMORE NATIONAL SECURITY LLC	SYSTEM AND METHOD FOR DETERMINING A PROBABILITY OF WELL SUCCESS USING STOCHASTIC INVERSION
EP2941532	2014	2015	CARBO CERAMICS INC, SANDIA CORP	ELECTRICALLY CONDUCTIVE PROPPANT AND METHODS FOR DETECTING, LOCATING AND CHARACTERIZING THE ELECTRICALLY CONDUCTIVE PROPPANT
WO2015134054	2014	2015	CARBO CERAMICS INC, SANDIA CORP	SYSTEMS AND METHODS FOR LOCATING AND IMAGING PROPPANT IN AN INDUCED FRACTURE
9250351	2015	2016	CARBO CERAMICS INC, SANDIA CORP	SYSTEMS AND METHODS FOR LOCATING AND IMAGING PROPPANT IN AN INDUCED FRACTURE
9394917	2014	2016	LOS ALAMOS NATIONAL SECURITY LLC	COOLING DEVICES AND METHODS FOR USE WITH ELECTRIC SUBMERSIBLE PUMPS
9434875	2014	2016	CARBO CERAMICS INC	ELECTRICALLY-CONDUCTIVE PROPPANT AND METHODS FOR MAKING AND USING

				SAME
WO2016100135	2015	2016	CARBO CERAMICS INC	ELECTRICALLY-CONDUCTIVE PROPPANT AND METHODS FOR MAKING AND USING SAME
9581004	2014	2017	GAS TECHNOLOGY INSTITUTE	HYDRAULIC FRACTURING SYSTEM AND METHOD
9732561	2016	2017	UNASSIGNED	METHOD AND APPARATUS FOR INCREASING WELL PRODUCTIVITY
9797402	2014	2017	CHEVRON USA INC, L. LIVERMORE NATIONAL SECURITY LLC	COOLING DEVICES AND METHODS FOR USE WITH ELECTRIC SUBMERSIBLE PUMPS
9811126	2011	2017	INTERNATIONAL BUSINESS MACHINES CORP	ENERGY EFFICIENT DATA CENTER LIQUID COOLING WITH GEOTHERMAL ENHANCEMENT
9862880	2014	2018	L. LIVERMORE NATIONAL SECURITY LLC	ENCAPSULATED PROPPANTS
9879175	2016	2018	L. LIVERMORE NATIONAL SECURITY LLC	ENCAPSULATED PROPPANTS
9879514	2017	2018	GAS TECHNOLOGY INSTITUTE	HYDRAULIC FRACTURING SYSTEM AND METHOD
9927549	2014	2018	CARBO CERAMICS INC, SANDIA CORP	SYSTEMS AND METHODS FOR LOCATING AND IMAGING PROPPANT IN AN INDUCED FRACTURE
9982523	2017	2018	GAS TECHNOLOGY INSTITUTE	HYDRAULIC FRACTURING SYSTEM AND METHOD
10018025	2017	2018	GAS TECHNOLOGY INSTITUTE	HYDRAULIC FRACTURING SYSTEM AND METHOD
10167422	2016	2019	CARBO CERAMICS INC	ELECTRICALLY-CONDUCTIVE PROPPANT AND METHODS FOR DETECTING, LOCATING AND CHARACTERIZING THE ELECTRICALLY-CONDUCTIVE PROPPANT
10487638	2018	2019	GAS TECHNOLOGY INSTITUTE	HYDRAULIC FRACTURING SYSTEM AND METHOD
10538695	2015	2020	CARBO CERAMICS INC, SANDIA CORP	ELECTRICALLY CONDUCTIVE PROPPANT AND METHODS FOR DETECTING, LOCATING AND CHARACTERIZING THE ELECTRICALLY CONDUCTIVE PROPPANT

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