The Influence of Patents in Twenty R&D Portfolios Funded by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy

Report prepared for:

U.S. Department of Energy (DOE)
Office of Energy Efficiency and Renewable Energy (EERE)
1000 Independence Avenue
Washington, DC 20585

Report prepared by:

1790 Analytics LLC
130 North Haddon Avenue
Haddonfield, NJ 08033

March 2022

Acknowledgements

This report traces the technological influence of R&D funded by the Office of Energy Efficiency and Renewable Energy (EERE) in the U.S. Department of Energy (DOE). It was prepared for DOE under Purchase Order No. 7454233 with Lawrence Berkeley National Laboratory (LBNL), Berkeley, California, USA. LBNL is operated by The Regents of the University of California under Prime Contract No. DE-AC02-05CH11231.

Yaw O. Agyeman, Program Manager, Lawrence Berkeley National Laboratory, provided technical oversight of the project. Jeff Dowd of EERE's Strategic Analysis Office (SA) was the DOE Project Manager.

Patrick Thomas of 1790 Analytics LLC was the principal researcher, analyst and author of the report. The author extends appreciation to the following EERE and LBNL staff who provided review comments of the draft study report:

- Yaw Agyeman, formerly Lawrence Berkeley National Laboratory
- Sam Baldwin, EERE Strategic Analysis Office
- Markus Beck, EERE Solar Energy Technologies Office
- Li Chenlin, EERE Bioenergy Technologies Office
- Jeff Dowd, EERE Strategic Analysis Office
- Phillip Dougherty, EERE Wind Energy Technologies Office
- Glen Drysdale, EERE Golden Field Office
- Tien Duong, EERE Vehicle Technologies Office
- Susan Hamm, EERE Geothermal Energy Technologies Office
- Hugh Ho, EERE Strategic Analysis Office
- Jennifer Jacobi, EERE Knowledge Management Services Office
- Sarah Keinbaum, EERE Vehicle Technologies Office
- Jack Mayernik, National Renewable Energy Laboratory (for EERE Building Technologies Office)
- Christopher Payne, Lawrence Berkeley National Laboratory
- Ammar Qusaibaty, EERE Solar Energy Technologies Office
- Jeannette Singsen, EERE Knowledge Management Services Office
- Lindsay Steele, Pacific Northwestern National Laboratory

Notice

Table of Contents

List of Figures

List of Tables

Executive Summary

This report provides a synthesis of a series of recent patent analyses carried out for the Office of Energy Efficiency & Renewable Energy (EERE) in the U.S. Department of Energy (DOE). These analyses trace the influence of patents in twenty different research portfolios selected by nine EERE research and development (R&D) offices for the period 1976-2018. In general, the twenty portfolios were selected because they either represent longstanding technology areas that comprise a substantial share of offices' R&D budgets, or are relatively nascent technologies with growth expected to continue into the future. Overall, the twenty portfolios correspond to approximately 60% of R&D funding from the nine EERE offices over the period 1976-2018. These twenty portfolios are listed below.

Additive Manufacturing	Solid State Lighting	Advanced Batteries
Algal Systems	Geothermal Energy	Advanced Combustion
Bioenergy Conversion	Fuel Cells	Lightweight Materials
Bioenergy Feedstocks	Hydrogen Production	Propulsion Materials
Domestic Appliances	Hydrogen Storage	Marine Hydrokinetics
HVAC	Concentrating Solar Power	Wind Energy
Water Heating	Solar Photovoltaics	

There are two main objectives of the analyses described in this report: to locate key patents awarded for EERE office-funded innovations; and to determine the extent to which EERE-funded research has influenced subsequent technological developments associated with other organizations. The study measures this influence primarily by tracing citation links between successive generations of patents.

The ***main finding*** from this report is:

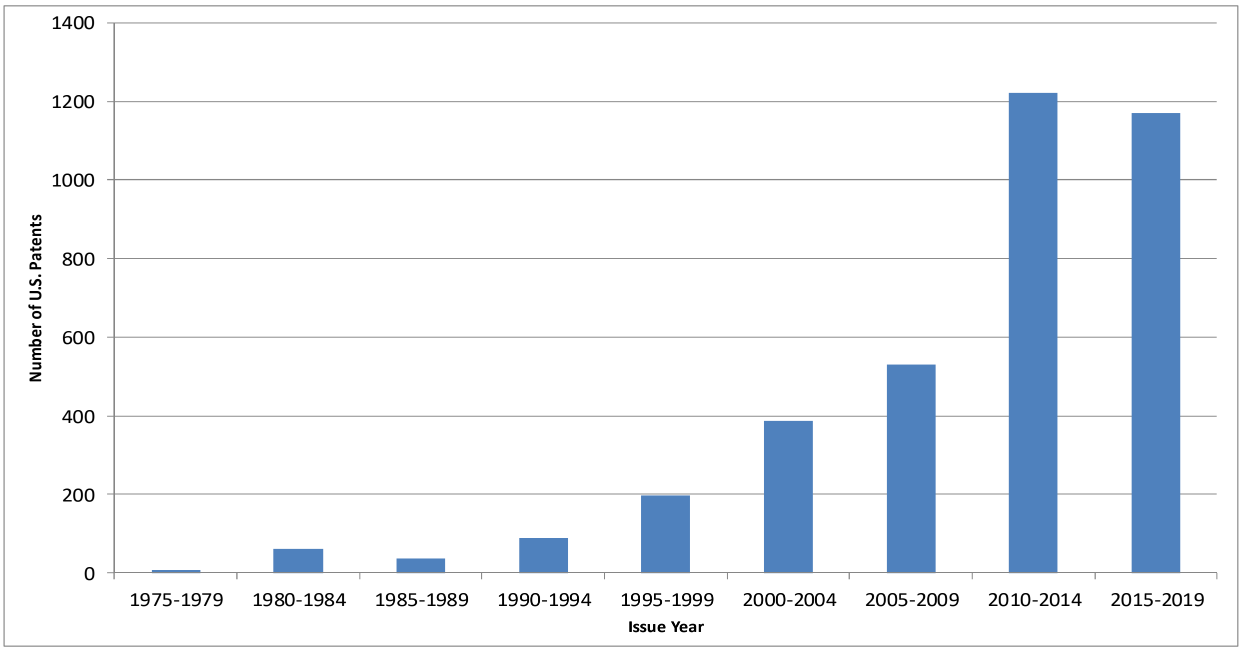
- **Patents in the twenty EERE R&D portfolios have had a strong influence on subsequent technological developments**. Although EERE-funded patents only represent a small percentage of the total patent universe in their respective technologies (0.6% overall), a Citation Index metric reveals that they have been cited 67% more frequently than expected. Patents in the 20 EERE-funded portfolios are also linked via citations to an average of almost 10% of subsequent patent families owned by the leading patenting organizations (98% of which are companies) in their respective technologies.

More detailed findings from this report include:

- **5,988 patents resulting from EERE funding were identified across the twenty portfolios**. These consist of 3,711 U.S. patents, 1,039 European Patent Office (EPO) patents, and 1,238 World Intellectual Property (WIPO) patent applications (referred to hereafter as "WIPO patents"). The 5,988 patents are grouped into 2,834 EERE-funded patent families, where each family contains all patents resulting from the same initial application (named the priority application). A family may contain patents from across multiple systems, for example U.S., EPO, and WIPO patents. Note that the data collection identified a further 1,738 EERE-funded patents in technologies other than those covered by the 20 portfolios. These patents are outside the scope of this study.

- **There was a sharp increase in EERE-funded patent activity after 2010**. Figure E-1 shows the number of granted U.S. patents associated with EERE-funded patent families in the twenty portfolios by issue year (i.e., the year these patents were granted). This figure reveals that there was little EERE-funded patent activity in the earliest time periods in the analysis. Six U.S. patents granted in 1975-1979 were funded by precursors of EERE (which was founded in 1981), followed by 61 EERE-funded patents in 1980-1984 and 38 in 1985-1989. The number of EERE-funded patents in the twenty portfolios then started to grow, slowly at first, reaching 530 in 2005-2009. It then grew to 1,222 patents in 2010-2014, an increase of 130% over 2005-2009. This is more than twice the 59% increase in total U.S. patents between these two time periods (see https://www.uspto.gov/web/offices/ac/ido/oeip/taf/us_stat.htm). There was a slight decrease to 1,170 U.S. patents in the twenty EERE-funded portfolios in 2015-2019, although data for this time period are incomplete (see note below Figure E-1).

Figure E-1 - Number of Granted U.S. Patents Associated with EERE-Funded Patent Families in Twenty Portfolios by Issue Year (5-Year Totals)

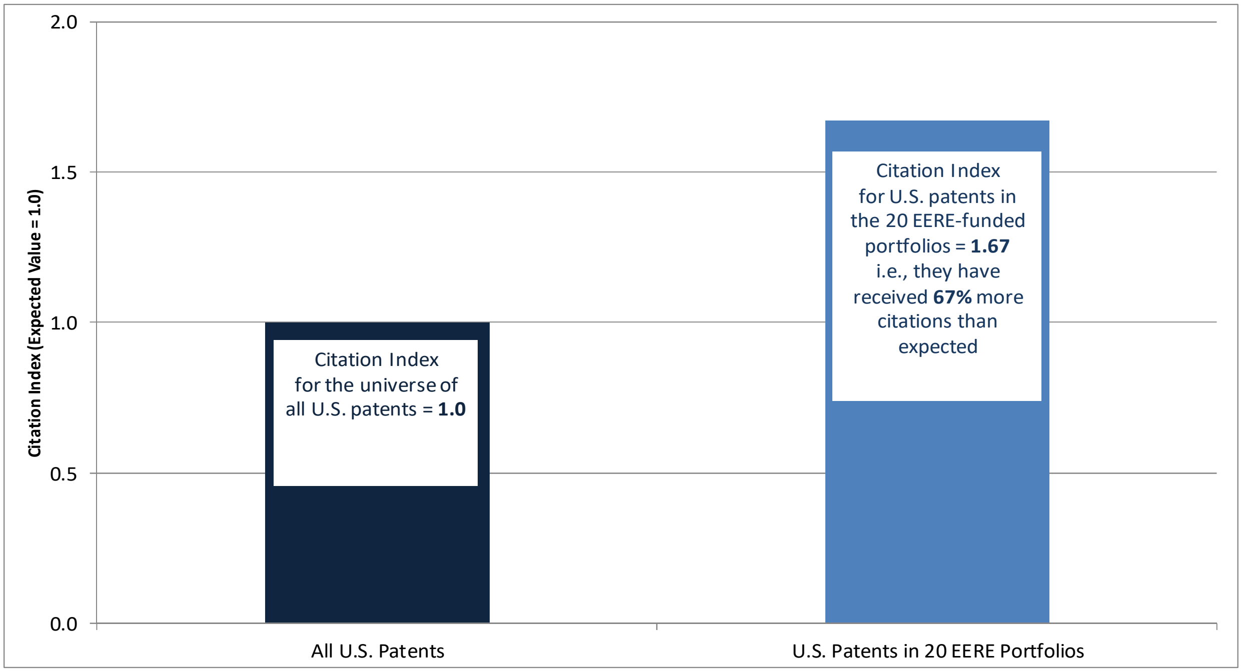


Note: Data for 2015-2019 are incomplete, since the primary data collection ended with 2018. Any 2019 patents in the 2015-2019 column are in families with pre-2019 patents. No new patent search for 2019 was conducted.

- **A significant time lag exists between project start dates and patent application/issue dates**. The mean time span from project start date to patent application date is 4.5 years, and the mean time span from project start date to patent issue date is 7.6 years. The corresponding median time spans are slightly lower at 4.0 years and 7.0 years, due to the somewhat skewed time span distributions. These figures are for U.S. patents resulting from EERE financial assistance projects, such as grants to companies and universities. The equivalent time spans for patents from DOE national labs are unknown.
- **EERE-funded patent families only represent a small percentage of total patent families in their respective technologies**. This percentage ranges from 0.1% to 3% across the 20 EERE-funded portfolios included in this analysis, with an overall average of 0.6% across all the portfolios. These low percentages are not surprising. The technologies include many major companies with large R&D budgets who produce patents, so EERE is only one source of funding among many.

- **EERE-funded patents have been cited 67% more frequently than expected, based on their age and technology**. Figure E-2 shows the overall Citation Index for U.S. patents in the 20 EERE-funded portfolios. The Citation Index is a normalized citation metric with an expected value of 1.0 (as shown in the left-hand bar of the figure). EERE-funded patents have a Citation Index of 1.67, meaning they have been cited 67% more frequently than the norm.

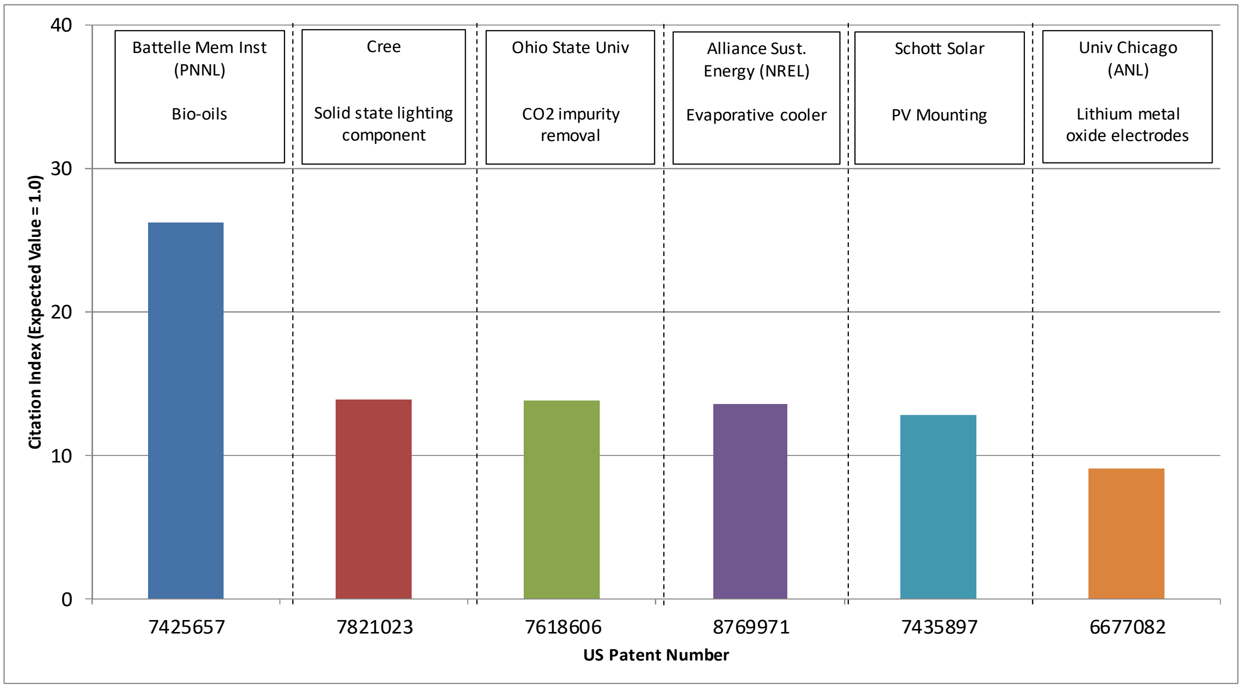
Figure E-2 Overall Citation Index of U.S. Patents in Twenty EERE-funded Portfolios



- **EERE-funded patents have had a notable influence on subsequent patents owned by the leading companies in their respective technologies.** On average, 9.8% of leading companies' patent families are linked via citations to earlier EERE-funded patents. The range for this statistic is from 0.1% to 30.7%, with several EERE-funded portfolios being linked to more than 20% of leading company patent families in their technology.

- **The 20 EERE-funded portfolios contain many highly-cited patents**. Figure E-3 shows examples of highly-cited patents from different EERE-funded portfolios (i.e., patents with high Citation Index values). They include NREL patents for bio-oils and evaporative cooling; a Cree patent for a solid-state lighting component; an Ohio State University patent for carbon dioxide removal; a Schott Solar patent for a photovoltaic mounting apparatus; and an Argonne National Laboratory patent for battery electrodes.

Figure E-3 – Examples of Highly-Cited EERE-funded Patents



- **Several DOE labs stand out in terms of their number of EERE-funded patents**. DOE Management and Operating Laboratory Contractors associated with large numbers of EERE-funded patents include: MRIGlobal (formerly Midwest Research Institute) and the Alliance for Sustainable Energy, both through their management of the National Renewable Energy Laboratory (NREL); Chicago-Argonne (Argonne National Laboratory); UT-Battelle (Oak Ridge National Laboratory); Sandia Corporation (Sandia National Laboratories); and Battelle Memorial Institute (Pacific Northwest National Laboratory). The University of California is also prominent, in part through its management of three DOE labs (Lawrence Berkeley National Laboratory; Lawrence Livermore National Laboratory; Los Alamos National Laboratory), and partly through research carried out at its own campuses.
- **A number of companies also have large portfolios of EERE-funded patent families**. Examples include General Motors (114 EERE-funded patent families), General Electric (105 families), Novozymes (91 families), and Caterpillar (63 families).
- **Green energy, green manufacturing, and green transportation are the primary focus of EERE-funded U.S. patents across the 20 portfolios**. This is based on the most common Cooperative Patent Classifications (CPCs) among EERE-funded U.S. patents (CPC is a system used by patent offices to classify patents based on their subject matter). The three most common CPCs across the 20 portfolios are:
    - Y02E: Green Energy - covers a number of renewable energy technologies including wind, solar, geothermal, clean combustion, fuel cells, hydrogen storage and production, and biofuels.
    - Y02P: Green Manufacturing - covers renewable energy applications across a range of industries, including chemicals, oil and gas, and agriculture.

  - Y02T: Green Transportation - relates to applications of renewable energy in road, rail, air, and sea transport.

- **Patent classifications related to specific technologies are also prominent among EERE-funded patents**. Examples include the following CPCs: H01M (Batteries); H01L (Semiconductor devices); C01B (Non-metallic elements); B01J (Chemical and physical processes); and C12N (Biochemistry).
- **EERE funding has helped fill research gaps not addressed by leading companies**. In this context, these research gaps are defined as specific technology areas where EERE-funded portfolios have a higher percentage of their patents than the portfolios associated with the leading companies. Examples include: large-scale concentrating solar power installations; comminution of crops and wood; absorption heating and cooling; hydrogen storage in metals; and downhole drilling technologies.
- **EERE-funded research is linked to later innovations related to renewable energy applications in transportation, manufacturing, energy generation, and building technologies**. This finding is based on an analysis starting with EERE-funded patents in the 20 portfolios, and tracing forwards in time through two generations of citations to these patents (i.e., patents that cite the EERE-funded patents as prior art; and patents that in turn cite these citing patents). This tracing exercise reveals that EERE-funded patents are linked via citations to subsequent innovations associated with applications of renewable energy across a wide range of transportation, manufacturing, energy, and building technologies.
- **EERE-funded research is also linked to subsequent spillover technology innovations beyond EERE's primary research focus areas**. Tracing forwards in time from the 20 portfolios through two generations of citations also reveals spillovers into technologies outside EERE's targeted technologies. These spillovers from EERE-funded research can be located in a wide range of industries, including chemicals, electronics, semiconductors, waste management, optics and advanced materials.

1.0 Introduction

This report provides a synthesis of a series of recent patent analyses conducted for the Office of Energy Efficiency & Renewable Energy (EERE) in the U.S. Department of Energy (DOE). These analyses trace the influence of patents in twenty different research portfolios selected by nine EERE offices for the period 1976-2018.[1] Appendix A contains a list of the individual EERE patent studies. This report presents the results generated by synthesizing the findings from these studies. The purpose of the patent analyses is twofold: to locate key patents awarded for EERE office-funded innovations; and to trace the influence of EERE-funded research on subsequent technological developments associated with other organizations. This influence is measured primarily by tracing citation links between successive generations of patents. It should be noted that the twenty EERE-funded portfolios correspond to approximately 60% of total R&D funding by the nine offices over the period 1976-2018.[2] As such, the results presented in this report should not be seen as reflecting all patents from these nine offices, nor all EERE-funded patents.

The report contains two main sections. The first of these sections describes the design and methodology of this patent study. This section includes a brief overview of the analytical tools employed in the analysis. It also describes the data sets used in the analysis, and the processes used to construct and link these data sets. The second section presents a summary of the results from across all twenty EERE-funded portfolios. These results are shown at the organizational level, in order to assess the overall influence of EERE-funded research. They are also presented at the level of individual patents, to highlight EERE-funded patents from each portfolio that have been particularly influential, and to locate spillovers from these patents into other technologies.

The analyses described in this report cover patents from three systems: the U.S. Patent & Trademark Office (U.S. patents); the European Patent Office (EPO patents); and the World Intellectual Property Organization (WIPO patent applications, referred to hereafter as "WIPO patents").[3] By covering multiple generations of citations across patent systems, this analysis allows for a wide variety of linkages between EERE-funded research and subsequent innovations. Examining all these linkages at the level of entire technologies involves a significant data processing effort, requiring access to specialist citation databases, such as those maintained at 1790 Analytics. As such, this study is more ambitious than many previous tracing studies, which have often studied more specific technologies or products.

> The results in this synthesis report do not make comparisons among the twenty EERE-funded portfolios, for example in terms of numbers of patents, number of citations, 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 presented in this report are not intended to be used to compare the EERE-funded portfolios.

[1] The earliest part of the study covers precursors to the U.S. Department of Energy, which was established in 1977.
[2] Percentage is based on EERE historical enacted appropriations from 1976 to 2018, provided by DOE and with inflation adjustment using 2018 GDP deflator. Funding data were obtained from several sources, including EERE Budget Search at https://www7.eere.energy.gov/office_eere/program_budget_formulation.php, past and present EERE budget at https://www.energy.gov/eere/past-and-present-eere-budget, and Congressional Budget documents.
[3] Note that the analyses do 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 EERE-funded 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.

2.0 Methodology

This section of the report provides an overview of the methodology used in the analysis. The overview is deliberately kept relatively brief, given that some readers may already be familiar with the methodology from the individual portfolio reports.[4] For readers who are interested, the appendices of this report contain more details on the various elements of the methodology.

Portfolios Included in the Analysis

The analyses described in this report cover a total of twenty EERE-funded research portfolios associated with nine different EERE offices. These portfolios were selected jointly by EERE technology managers and the DOE project manager of this study. Table 1 contains a list of these portfolios.

Table 1 – List of EERE Research Portfolios Included in the Analysis

EERE Office	Research Portfolio
Advanced Manufacturing Office (AMO)	Additive Manufacturing
Bioenergy Technologies Office (BETO)	Algal Systems
	Bioenergy Conversion
	Bioenergy Feedstocks
Building Technologies Office (BTO)	Domestic Appliances
	HVAC
	Water Heating
	Solid State Lighting
Geothermal Technologies Office (GTO)	Geothermal Energy
Hydrogen and Fuel Cell Technologies Office (HFTO)	Fuel Cells
	Hydrogen Production
	Hydrogen Storage
Solar Energy Technologies Office (SETO)	Concentrating Solar Power
	Solar Photovoltaics
Vehicle Technologies Office (VTO)	Advanced Batteries
	Advanced Combustion
	Lightweight Materials
	Propulsion Materials
Water Power Technologies Office (WPTO)	Marine Hydrokinetics
Wind Energy Technologies Office (WETO)	Wind Energy

Identifying Patents in Each EERE-funded Portfolio

The analysis first defines the twenty EERE-funded research portfolios, in terms of the patents contained within them. Outlined below are the four steps used to identify patents in each EERE-funded portfolio. More details of each of these steps are provided in Appendix B of this report.

[4] Copies of the individual portfolio reports, which cover the methodology in more detail, can be found at https://www.energy.gov/eere/analysis/eere-evaluation-publications, using '2021' under 'year' as a search parameter.

Step 1: Define the universe of DOE-funded U.S. patents;

Step 2: Select the patents in this DOE patent universe (from Step 1) that are relevant to the subject technology (using a patent filter consisting of keywords and patent classifications);

Step 3: Determine which of the technology-relevant DOE-funded patents (from Step 2) were funded by the EERE office in question; and

Step 4: Take the list of technology-relevant EERE-funded patents (from Step 3), and add to this list other members of the patent families[5] to which these EERE-funded patents belong.

The output of this four-step process is a list of EERE-funded U.S., EPO, and WIPO patents in each of the twenty portfolios, grouped according to their patent family.

Tracing the Influence of EERE-funded Research Portfolios

Having defined the twenty EERE-funded patent portfolios, and evaluated various characteristics of them – including trends, assignees, and technology distributions – the next step is to trace the influence of these portfolios on subsequent technological developments. This influence tracing is based largely upon citation links between successive generations of patents. In simple terms, the idea behind this analysis is to determine how frequently EERE-funded patents have been cited as prior art by subsequent patents. This helps to determine the extent to which EERE-funded research forms a foundation for subsequent innovations. A more detailed discussion of this influence tracing exercise, plus a background on the use of citations to measure and trace the influence of patents, can be found in Appendix C of this report.

The influence tracing is implemented using two distinct approaches, both of which include prior art citations listed on U.S., EPO and WIPO patents. The first tracing approach ("forward tracing") starts with the EERE-funded patents in a given portfolio, and traces forwards in time through two generations of citations (i.e., patents that cite the EERE-funded patents as prior art; and patents that in turn cite these citing patents). Forward tracing examines the influence of EERE-funded patents in general. This tracing is not restricted to subsequent patents in the same technology, since the influence of a body of research may extend beyond its immediate field. For example, a geothermal energy patent may influence later developments in mining or oil and gas exploration.

The second tracing approach ("backward tracing") starts with patent families assigned to the leading patenting organizations in a given technology. These leading organizations are defined as the ten (and – in a few technologies – twelve) organizations with the largest number of patent families in the technology. They are identified by applying the same filters used to identify relevant EERE-funded patents (see Step 2 above), this time to the universe of all patents. These organizations may include companies, universities, and non-profit organizations. That said, in this study, 98% of the leading organizations are companies. For clarity, the term "leading

[5] A "patent family" contains all patents resulting from the same initial application (named the priority application). A family may include multiple patents from across patent systems, for example U.S., EPO, and WIPO patents. See Appendix B for a more detailed discussion of patent families.

companies" is thus used hereafter in this report, rather than the more cumbersome "leading patenting organizations".

The backward tracing takes the patents owned by these leading companies and traces backwards in time through two generations of citations (i.e., patents cited by the leading company patents as prior art; and patents that are in turn cited by these cited patents). It then assesses how many of the earlier patents are associated with EERE funding. As such, backward tracing examines the influence of EERE-funded patents on innovations associated with leading companies in the corresponding technology. For example, the analysis assesses the influence of EERE-funded wind energy patents on later patents assigned to leading wind energy companies.

Metrics Used in the Analysis

Table 2 contains a list of the metrics used in this report. These metrics are divided into four main groups – trends; assignees; technology distributions; and influence tracing. Findings for each of these four groups of metrics can be found in the Results section of the report.

Table 2 – List of Metrics Used in the Analysis

Metric
Trends
• Overall number of EERE-funded granted patents and patent families
• Number of EERE-funded patent families by year of priority application
• Number of EERE-funded granted U.S. patents by issue year
Relating Project Start Dates to Patent Outputs
• Pendency (time from application to issue) for EERE-funded patents
• Time from EERE project start date to patent application date
• Time from EERE project start date to patent issue date
Assignee Metrics
• Assignees with largest number of EERE-funded patent families
Technology Metrics
• Cooperative Patent Classification (CPC) distribution for EERE-funded patent families
• Cooperative Patent Classification (CPC) distribution for EERE-funded patent families across two time periods
• Research areas where EERE-funded patents have a greater focus than leading companies
Influence Tracing Metrics
• Overall Citation Index for EERE-funded U.S. patents
• Average Citation Index for U.S. patents in each EERE-funded portfolio
• Individual EERE-funded U.S. patents with high Citation Index values
• Percentage of leading company patent families linked to each EERE portfolio
• Leading company linked most extensively to each EERE portfolio
• Companies linked via citations to largest number of EERE-funded patent families overall
• Number of patent families linked via citations to EERE-funded patents by patent classification
• Spillovers from EERE-funded portfolios into other technologies
• EERE-funded patent families with extensive citation links (spillovers) to other technologies

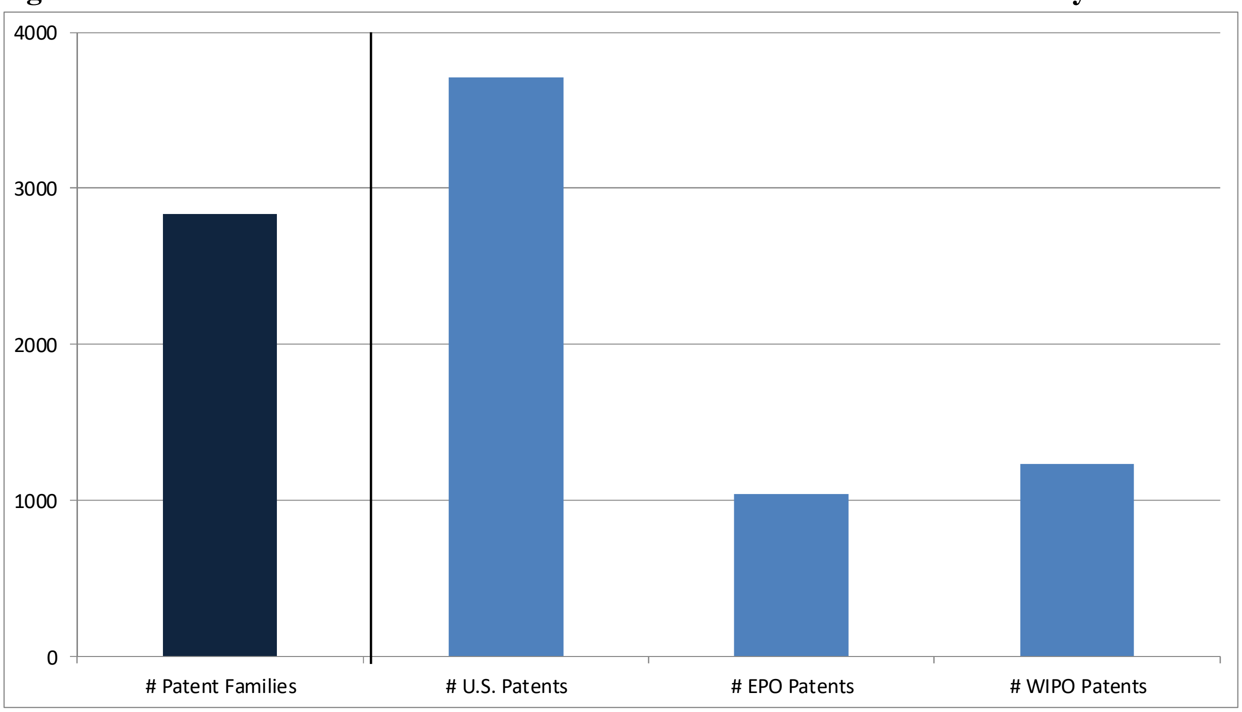
3.0 Results

This section of the report presents the results generated by synthesizing the findings from the twenty individual portfolio analyses. The results are divided into two main sections. The first section examines trends in EERE-funded patenting over time, identifies the leading assignees on EERE-funded patents, and assesses the distribution of these patents across technologies. This section also looks at the relationship between the start date for EERE-funded projects and their associated patent outputs, in order to provide EERE offices with an idea of how long they should expect these time lags to be in general. The second section then reports the results of an analysis tracing the influence of EERE-funded patents, both overall and on innovations associated with leading companies.

Trends in EERE-funded Patenting

Figure 1 shows the total number of patent families funded by EERE across all twenty portfolios included in the analysis. This figure reveals that there are a total of 2,834 EERE-funded patent families in the twenty portfolios. These families contain 3,711 U.S. patents, 1,039 EPO patents, and 1,238 WIPO patent applications ("WIPO patents"). Hence, in total, the 2,834 EERE-funded patent families contain 5,988 patents (U.S., EPO and WIPO combined).[6]

Figure 1 – Number of EERE-funded Patents and Patent Families across Twenty Portfolios



[6] In this analysis, patents in the DOE-funded universe are only classified as EERE-funded if a definite link to EERE funding can be established (see Appendix B for details). Especially for older patents, definitive funding information at the office level may be unavailable, because records are less comprehensive, and there is limited access to the inventors and program managers involved. Patents whose funding source within DOE could not be established are excluded from the EERE-funded portfolios, even though some of these patents may in fact have been funded by EERE. As such, the results reported here may underestimate the influence of EERE-funded research.

It should be noted that the patents in the twenty EERE-funded portfolios represent a significant percentage of all EERE-funded patents, but they do not constitute all such patents. For example, as part of the process of researching contract numbers to determine which DOE-funded patents were funded by EERE, a further 1,738 EERE-funded patents were identified, beyond the 5,988 EERE-funded patents included in this analysis. These additional patents are in technologies other than those covered by the 20 portfolios, and result from projects funded by EERE via financial assistance (i.e., through grants to companies and universities). There are also an unknown number of DOE national lab patents in technologies beyond the twenty portfolios that may have been funded by EERE.[7] Hence, the results presented below should not be construed as representing all EERE-funded patents.

Figure 1 reveals that EERE funding is connected to thousands of patents and patent families. However, it is important to recognize that EERE-funded patent families only represent a small percentage of total families in their respective technologies. This percentage ranges from 0.1% to 3% across the twenty EERE-funded portfolios, with an overall average of 0.6% across all the portfolios. Only three EERE-funded portfolios (bioenergy feedstocks, geothermal energy, and hydrogen storage) represent more than 2% of the total patent families in their respective technologies. These low percentages across the twenty portfolios are not surprising, since many of the technologies include major companies with very large R&D budgets, so EERE is only one source of research funding among numerous other organizations.

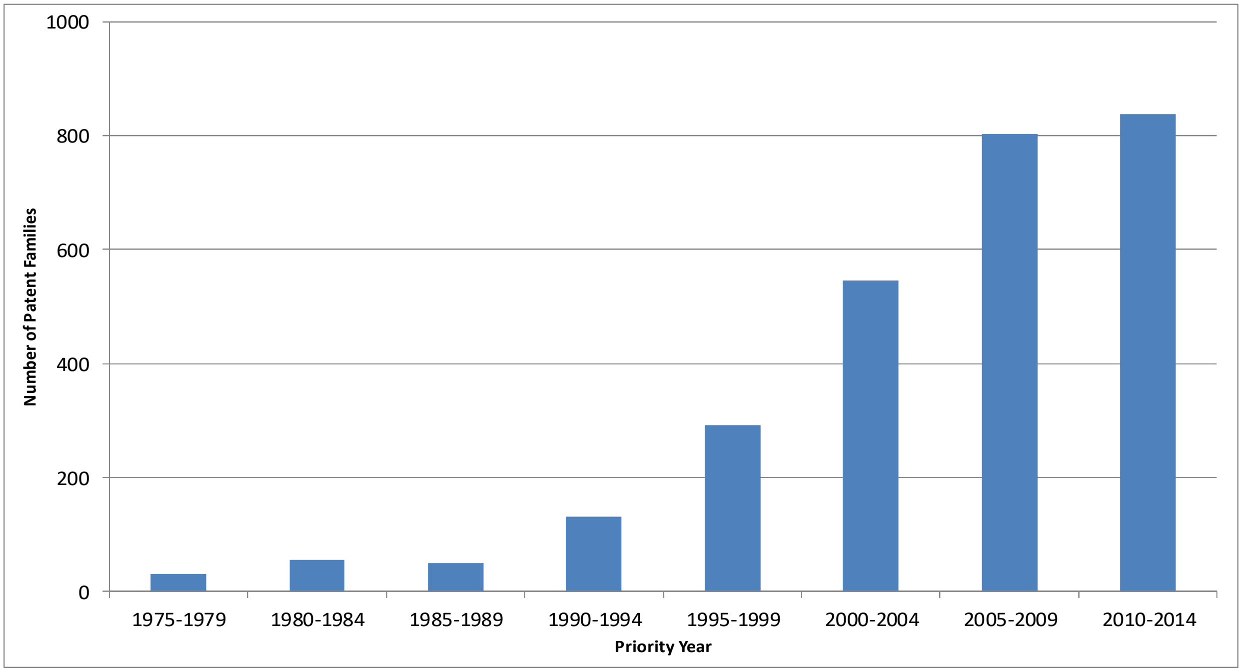
Figure 2 shows the number of patent families funded by EERE across the twenty portfolios by priority year (i.e., the year of the first application filed in each family). This figure reveals that EERE-funded patenting was relatively sparse in the earliest time periods in the analysis. In total, there were 30 patent families filed in 1975-1979 that were funded by precursors of EERE (with EERE itself being founded in 1981). This was followed by 56 EERE-funded patent families in 1980-1984 and 50 families in 1985-1989. EERE-funded patenting has increased markedly since those early time periods. More than 800 EERE-funded patent families were filed in both 2005-2009 (804) and 2010-2014 (838). Hence, almost 30 times as many EERE-funded patent families were filed in 2010-2014 than in 1975-1979 (and over sixteen times as many as in 1985-1989).

Figure 3 shows the number of granted U.S. patents associated with the EERE-funded patent families in the twenty portfolios by issue year (i.e., the year these patents were granted). This figure follows a similar pattern to Figure 2, which focused on patent families. Again, there is little EERE-funded patent activity in the earliest time periods in the analysis, with six U.S. patents granted in 1975-1979 that were funded by precursors of EERE, followed by 61 EERE-funded patents in 1980-1984 and 38 in 1985-1989. The number of patents then started to grow, relatively slowly at first, reaching 530 in 2005-2009. It then grew to 1,222 patents in 2010-2014, an increase of 130% over 2005-2009. This is more than twice the 59% increase in total U.S. patents between these two periods.[8] There was then a slight decrease to 1,170 U.S. patents in 2015-2019, although data for this time period are incomplete (see note below Figure 3).

[7] In total, 65% of the 5,988 EERE-funded patents in the twenty portfolios are from financial assistance projects, versus 35% from DOE national labs. Given that the levels of these two types of EERE funding have been roughly equivalent, the higher percentage of financial assistance patents may reflect the difficulty in determining funding sources within DOE for national lab patents.

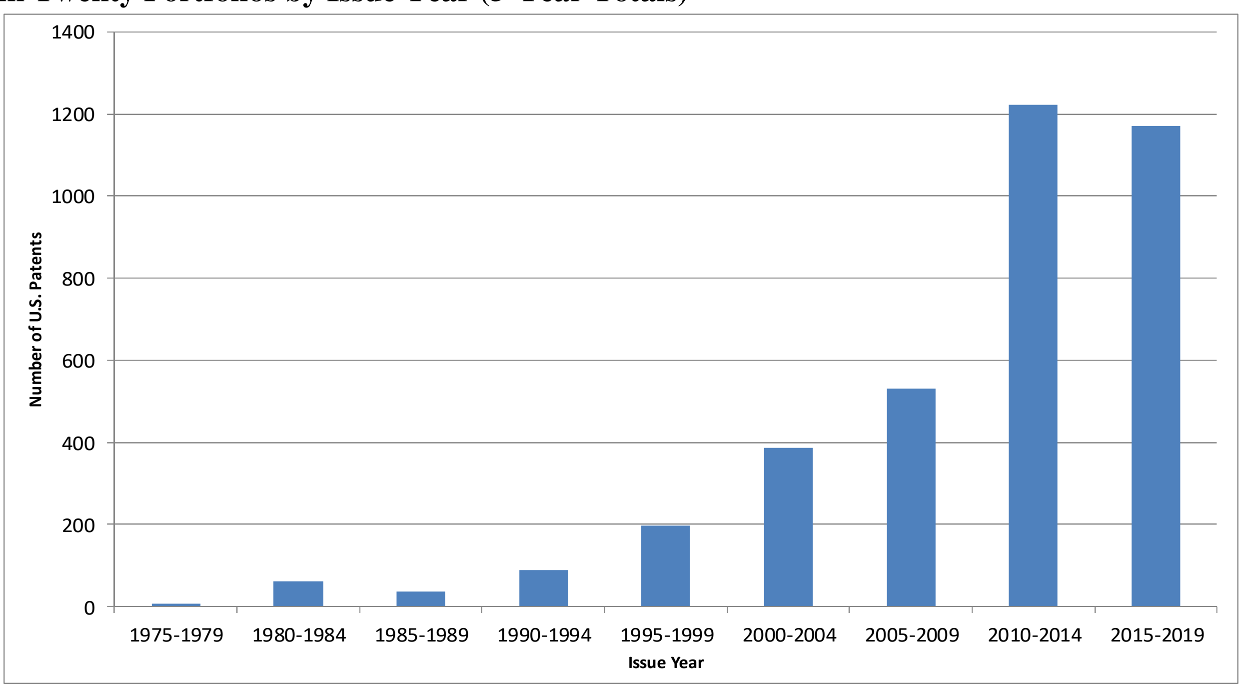
[8] See https://www.uspto.gov/web/offices/ac/ido/oeip/taf/us_stat.htm

Figure 2 - Number of EERE-funded Patent Families across Twenty Portfolios by Priority Year (5-Year Totals)



Note: The primary data collection for this study ended with patents issued through 2018. Given the time lags associated with the patenting process (see discussion of patent pendency below), patent family data for the 2015-2019 period are incomplete. Any patent families filed in 2019 are excluded, and so are families filed before the end of 2018 that had not produced any granted patents through 2018. To avoid confusion, Figure 2 does not show data for 2015-2019, since such data would only represent a fraction of the patent familes filed during that time period.

Figure 3 - Number of Granted U.S. Patents Associated with EERE-Funded Patent Families in Twenty Portfolios by Issue Year (5-Year Totals)

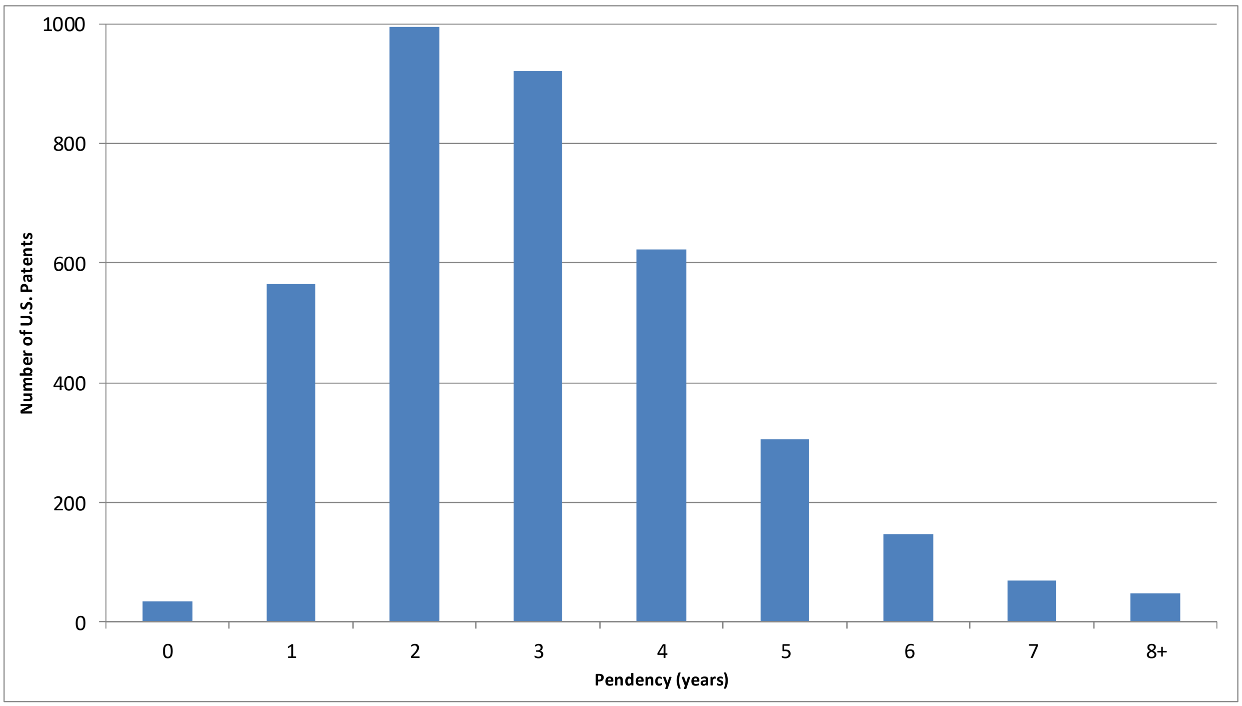


Note: Data for 2015-2019 are incomplete, since the primary data collection ended with 2018. Any 2019 patents in the 2015-2019 column are in families with pre-2019 patents. No new patent search for 2019 was conducted.

Relating EERE Project Start Dates to Patent Outputs

Comparing Figure 2 and Figure 3 shows the effect of time lags in the patenting process, with the increase in patent families filed in 2005-2009 and 2010-2014 feeding through into the peak in granted U.S. patents in 2010-2014 and 2015-2019. For a different view of the time lags associated with patents, Figure 4 shows the pendency for all EERE-funded U.S. patents in the analysis (i.e., the number of years between when each patent was applied for, and subsequently granted). This figure reveals that the bulk of EERE-funded U.S. patents have a pendency of 2-3 years, although there is a range showing pendency of less than one year for a small number of patents, and extending beyond eight years for others. The overall mean pendency is 2.99 years, and the median is three years. EERE offices should thus anticipate an average of approximately three years from when a U.S. patent is filed until it is granted. That said, this time period may be somewhat lower moving forward, as the overall mean pendency at the USPTO has been reduced in recent years (see https://www.uspto.gov/blog/director/entry/uspto_meets_critical_goals_to).

Figure 4 – Pendency (years from application to issue date) for EERE-funded U.S. Patents



Beyond pendency statistics, for EERE-funded patents there are also time gaps from when projects start, to when patent applications are filed. Figure 5 shows these gaps, albeit using only a subset of EERE patents, due to data availability. Specifically, this figure shows the time in years from project start date to application date for 1,505 granted U.S. patents resulting from EERE financial assistance projects. These are projects funded by EERE as grants to organizations such as companies and universities, rather than to DOE national labs. This figure reveals that over half of these patents (775 out of 1,505) have a gap of between two and four years from project start date to application date. The mean time gap is 4.5 years, with this mean being boosted by a number of patents with very long gaps (some of which may result from umbrella project numbers incorporating multiple research efforts). The median time gap is thus slightly lower at four years.

Figure 5 - Time (in Years) from Project Start Dates to Patent Application Dates for U.S. Patents Funded by EERE via Financial Assistance

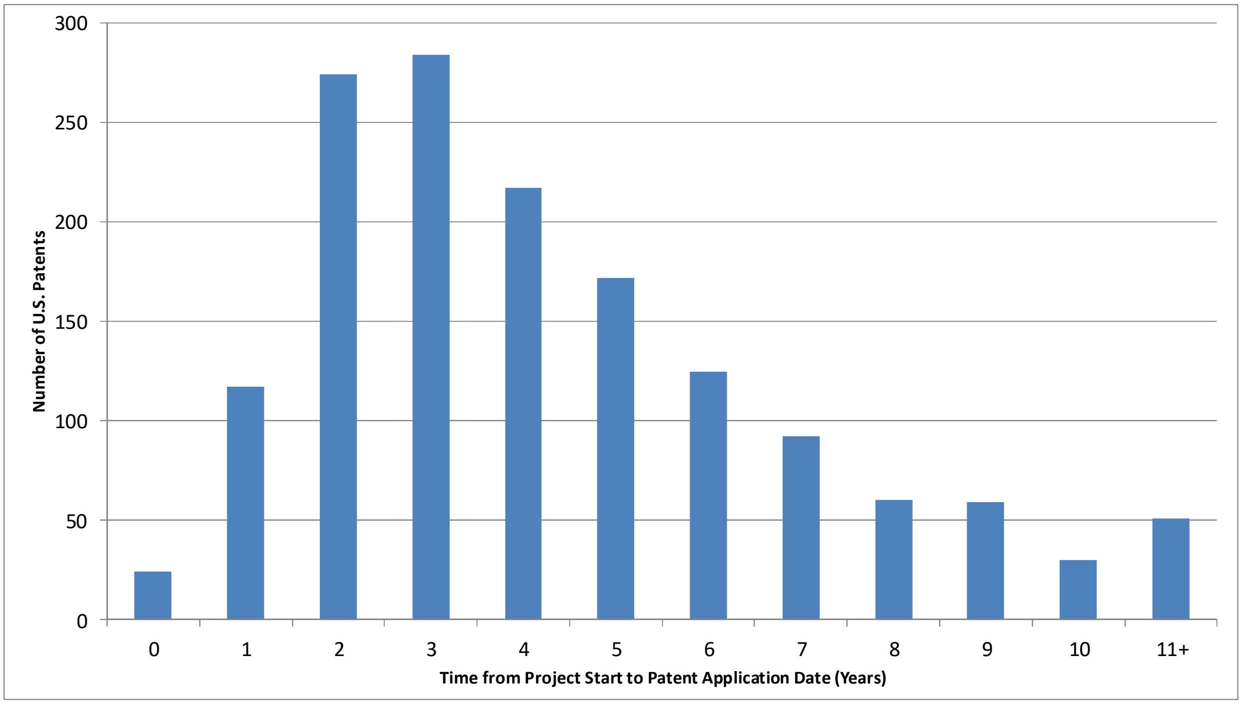
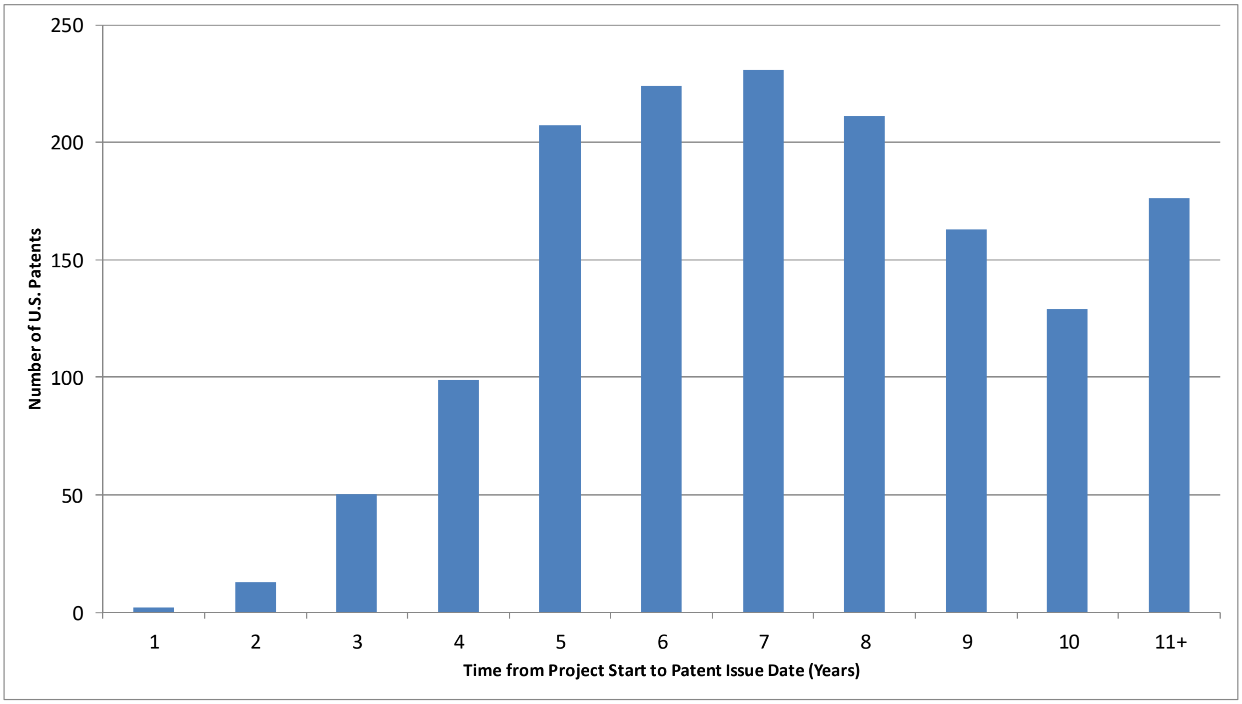


Figure 4 and Figure 5 highlight two distinct time spans – i.e., the time from project start date to patent application (Figure 5), and the time from patent application to patent issuance (Figure 4). The start date-application date time span largely reflects the process of developing an innovation, plus the time to prepare and submit the associated patent application. Meanwhile, the application date-issue date time span is more concerned with the legal and bureaucratic processes associated with having the patent application examined and granted (if it is successful in this examination). Taken together, these time spans determine the length of time between the date on which a project starts, and the date on which a patent resulting from the project is granted.

Figure 6 shows the time span from project start date to issue date for the 1,505 granted U.S. patents funded by EERE via financial assistance referred to above. This figure reveals that 89% of these patents (1,341 out of 1,505) were issued at least five years after the project start date, with the largest concentration being in the 5-8 year range (873 out of 1,505, or 58%). The mean time span from project start date to patent issue date is 7.6 years, with the median being slightly lower at seven years due to the somewhat skewed distribution. One takeaway from Figure 6 is that, for financial assistance projects, EERE offices should not expect these projects to result in granted patents within their first few years. Instead, between time associated with the innovation process, and the time related to patent examination, EERE offices should anticipate that it will be a number of years from when a project starts, to when it generates granted patents.

Figure 6 - Time (in Years) from Project Start Dates to Patent Issue Dates for U.S. Patents Funded by EERE via Financial Assistance

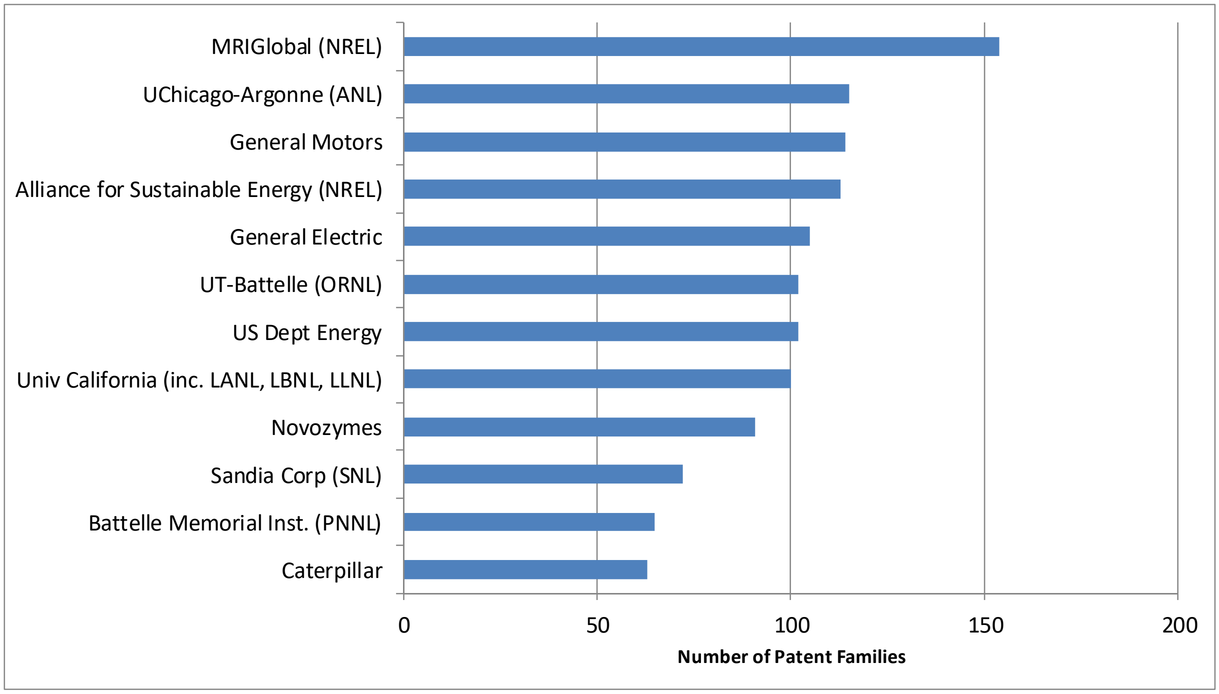


Leading Assignees on EERE-funded Patent Families

Figure 7 shows the assignees with the largest number of patent families funded by EERE across the twenty portfolios included in the analysis.[9] This figure is an interesting mix of DOE Management and Operating Laboratory Contractors ("M&O contractors") and large companies. It is headed by MRIGlobal (formerly Midwest Research Institute), which has a total of 154 EERE-funded patent families across the twenty portfolios. Most of these patent families result from MRIGlobal's former management of the National Renewable Energy Laboratory (NREL). MRIGlobal is one of two assignees in Figure 7 associated with NREL, the other being the Alliance for Sustainable Energy, a joint venture between MRIGlobal and Battelle that is the current manager of NREL. It has 113 EERE-funded patent families across the twenty portfolios. Hence, NREL has played an important role in these EERE-funded research portfolios.

[9] The assignee is the owner of the property rights in a patent. When a company funds internal research, the rights to any patented inventions resulting from this research are typically assigned to (i.e., owned by) the company itself. The assignee question is somewhat more complicated for a government agency, 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. Many patents from Pacific Northwest National Laboratory are assigned to Battelle Memorial Institute, while many Lawrence Livermore National Laboratory patents are assigned to the University of California. A further complication is that DOE does not only fund research in its own labs, it also funds extramural research carried out by organizations such as companies and universities. If this research results in patented inventions, these patents are typically assigned to the organizations that carried out the research, following legislation such as the Bayh-Dole Act of 1980.

Figure 7 - Assignees with Largest Number of EERE-funded Patent Families across Twenty Portfolios



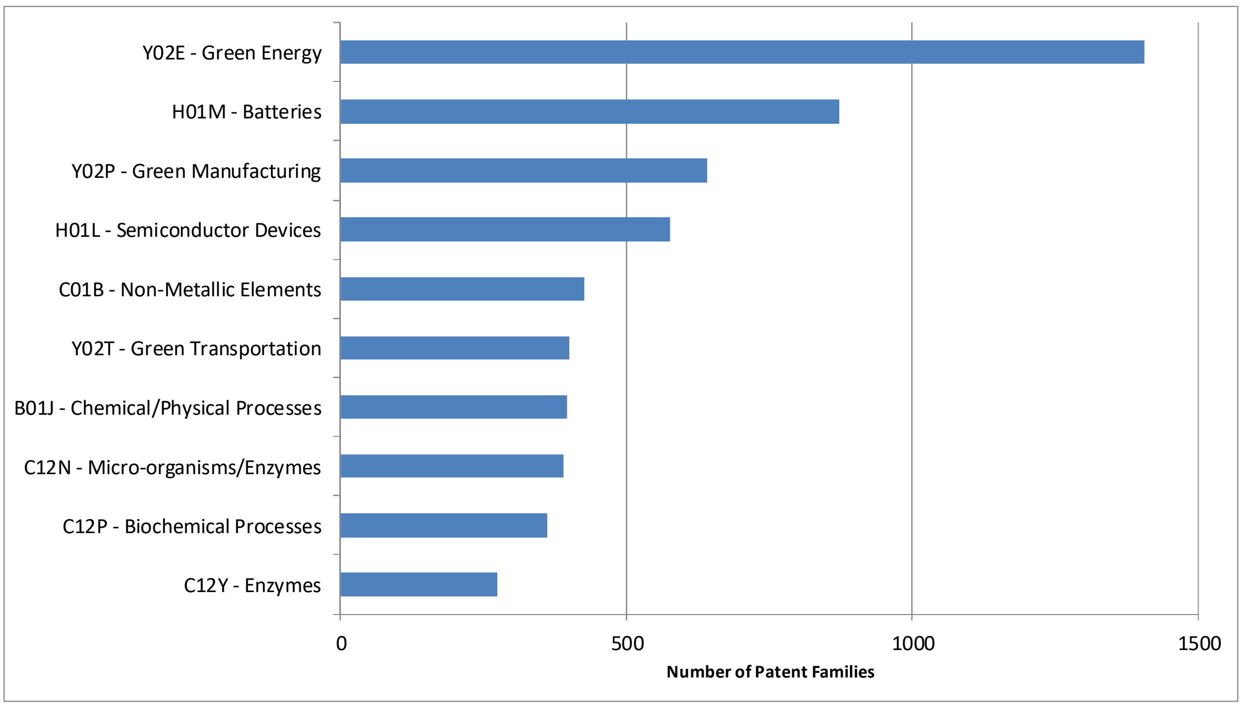
There are a number of other DOE M&O contractors featured in Figure 7. They include UChicago-Argonne (through its management of Argonne National Laboratory), UT-Battelle (Oak Ridge National Laboratory), Sandia Corporation (Sandia National Laboratories) and Battelle Memorial Institute (Pacific Northwest National Laboratory). The University of California is also prominent in Figure 7, in part through its management of three DOE labs (Lawrence Berkeley National Laboratory; Lawrence Livermore National Laboratory; Los Alamos National Laboratory), and partly through research carried out at its own campuses. It is also worth noting that DOE itself appears in Figure 7. Patents may be assigned to DOE for various reasons, including where the inventors are federal employees (e.g., from the National Energy Technology Laboratory); 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.

Beyond DOE M&O contractors and DOE itself, there are also a number of companies featured in Figure 7. The most prominent of these companies is General Motors, with 114 patent families funded by EERE across the twenty portfolios. Not surprisingly, many of these families are in vehicle-related portfolios, as are the 63 patent families assigned to Caterpillar, which appears at the bottom of the figure. General Electric is also prominent in Figure 7, with 105 EERE-funded families, which are spread across a variety of the twenty portfolios. The other company in Figure 7 is Novozymes, with 91 EERE-funded patent families, mostly related to bioenergy.

Technology Distribution of EERE-funded Patents

Figure 8 shows the most common Cooperative Patent Classifications (CPCs) among EERE-funded U.S. patents across the twenty portfolios.[10] This figure thus reflects the main technological concentrations of EERE-funded patents across these portfolios in general (although the result depicted in this figure is driven primarily by the larger portfolios, containing the highest numbers of patents). The most common CPC across the twenty portfolios is Y02E, which is concerned with Green Energy.[11] There are 1,405 patent families with this CPC attached. It is something of a catch-all CPC, and covers a range of renewable energy technologies including wind, solar, geothermal, clean combustion, fuel cells, hydrogen storage and production, and biofuels. It is thus not surprising that it is at the head of Figure 8, since these technologies are the focus of various portfolios included in this study.

Figure 8 – Most Common Cooperative Patent Classifications Among EERE-funded U.S. Patents in Twenty Portfolios



There are also two other somewhat generic renewable energy CPCs in Figure 8. The first is Y02P, which is related to Green Manufacturing[12], with 642 EERE-funded patent families in the twenty portfolios having this CPC attached. This CPC covers renewable energy applications across a range of industries, including chemicals, oil and gas, metals and minerals

[10] 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.

[11] The labels attached to CPCs in this chart (and in other CPC-related charts in this report) are shorthand for the actual CPC titles, which can be very long and detailed, and thus unwieldy to show in chart format. For example, the CPC Y02E, which is labeled "Green Energy" in Figure 8, is actually titled "Reduction of Greenhouse Gas (GHG) Emissions, Related to Energy Generation, Transmission or Distribution".

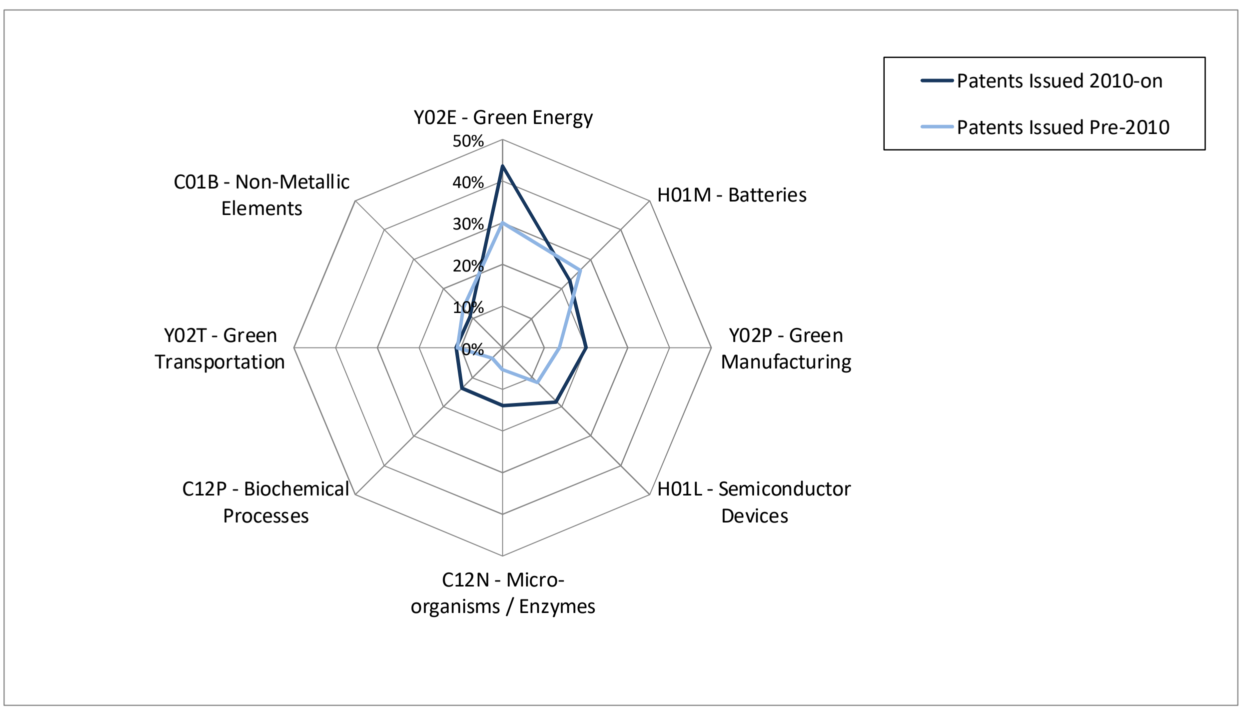
[12] The full name of this CPC is "Climate change mitigation technologies in the production of processing of goods".

manufacturing, consumer products, and agriculture. The other renewable energy CPC in Figure 8 is Y02T. This CPC is concerned with Green Transportation[13], and covers applications of renewable energy in road, rail, air, and sea transport. There are 400 EERE-funded patent families across the twenty portfolios with this CPC attached.

Figure 8 also contains a number of CPCs related to specific technologies. The most prominent of these is H01M (Batteries), with 873 EERE-funded patent families across the twenty portfolios. Also prominent in Figure 8 is CPC H01L (Semiconductor Devices) with 577 such patent families. This CPC contains patents across a range of EERE-funded portfolios, notably solar photovoltaics and solid state lighting. There are also CPCs related to non-metallic elements, such as hydrogen (C01B); chemical and physical processes such as material handling and catalysis (B01J); plus a number of CPCs related to biochemistry and microbiology (C12N; C12P and C12Y). These are examples of technologies associated with the twenty portfolios in the analysis.

Figure 9 again shows the most common CPCs among EERE-funded U.S. patents in the twenty portfolios. However, it divides these patents into two groups according to their issue dates – those granted prior to 2010, and those granted from 2010 onwards. The purpose of Figure 9 is thus to highlight changes over time in the CPC distribution of EERE-funded patents. This figure shows that the most common CPC in both time periods is Y02E (Green Energy), with 30% of pre-2010 patents and 44% of patents from 2010-on having this CPC attached. The figure also reveals that recent years have seen a greater focus on CPCs related to semiconductor devices (H01L, with 18.3% of patents), and biochemistry (C12N and C12P, with 13.8% and 13.7% of patents respectively).

Figure 9 – Percentage of EERE-funded U.S. Patents in Twenty Portfolios by CPC across Two Time Periods



[13] The full name of this CPC is “Climate change mitigation technologies related to transportation”.

The CPCs in Figure 8 and Figure 9 reflect technologies at a relatively high level – semiconductors, biochemistry, batteries, etc. At the level of individual portfolios, it is also possible to examine the CPC distribution of EERE-funded patents at a more granular level. For example, it is interesting to identify specific research areas where EERE-funded patents have a greater focus (in terms of percentage of patent families in a given CPC) than the patents of leading companies in the corresponding technology. In some cases, these may be instances of EERE funding helping to fill a research gap not addressed extensively by the leading companies. Table 3 contains examples of such research areas for each of the twenty EERE portfolios. For example, in concentrating solar power, EERE-funded patents are focused much more on large scale installations than the patents of leading companies. Similarly, EERE-funded geothermal patents have a greater focus on downhole technologies such as surveying and drilling than the patents assigned to the leading companies. Note that three of the EERE-funded portfolios in Table 3 (additive manufacturing; marine hydrokinetics; advanced batteries) are concentrated in research areas that are similar to the patents assigned to leading companies in these technologies.

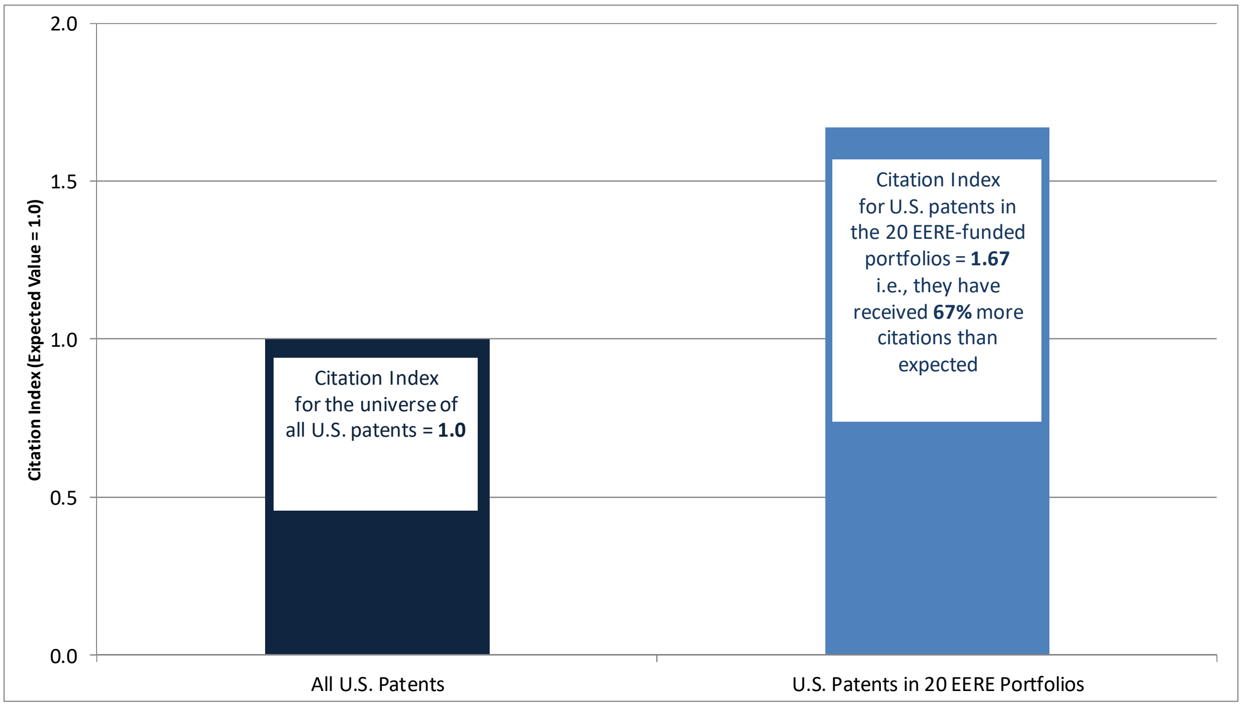
Table 3 – Examples of Research Areas where EERE-funded Patents are More Concentrated than Patents Assigned to the Leading Companies

EERE Portfolio	Technology Focus
Additive Manufacturing	N/A (EERE patents are advancing similar research areas to the leading companies)
Algal Systems	cell lysis; ethanol production
Bioenergy Conversion	specific bioenergy substances (e.g., cellulosic bio-ethanol)
Bioenergy Feedstocks	cutting fibrous materials; comminution for crops and wood
HVAC	absorption heating/cooling; heat exchanger components; AC desiccants
Appliances	absorption and magnetic refrigeration
Water Heating	absorption-based heating
Fuel Cells	polymeric electrolytes; membrane electrode assemblies; platinum-based alloys
Hydrogen Production	integration of hydrogen production with fuel cells
Hydrogen Storage	hydrogen storage in metals/alloys and solid composites
Geothermal	downhole technology (surveying, drilling etc.)
Marine Hydrokinetics	N/A (EERE patents are advancing similar research areas to the leading companies)
Solar PV	back-junction PV cells; applications of PV in buildings
Concentrating Solar Power	large-scale CSP installations
Solid State Lighting	organic solid state devices
Advanced Batteries	N/A (EERE patents are advancing similar research areas to the leading companies)
Advanced Combustion	exhaust gas recirculation
Propulsion Materials	alloys and non-metallic elements
Lightweight Materials	carbon fibers; plastics; soldering/welding
Wind Energy	nacelle technology

Tracing the Influence of EERE-funded Patents

One overall measure of the influence of patents on subsequent technological developments is the Citation Index.[14] Figure 10 shows the overall Citation Index for U.S. patents in the twenty EERE-funded portfolios. The left-hand bar in this figure represents all U.S. patents, and equals one – i.e., the expected value for all patents combined. The right-hand bar is the Citation Index for EERE-funded patents and equals 1.67. This shows that, taking into account their age and technology distribution, EERE-funded patents in the twenty portfolios have been cited as prior art 67% more frequently than expected. As a comparison, the patents of leading companies in the twenty technology areas have a Citation Index of 1.16 (i.e. 16% more citations than expected).

Figure 10 – Overall Citation Index of U.S. Patents in Twenty EERE-funded Portfolios



It should be noted that the high Citation Index for EERE-funded patents in Figure 10 is not the result of a small number of highly-cited portfolios. Indeed, almost all of the twenty EERE portfolios have Citation Index values above one (i.e., they have been cited as prior art more frequently than expected). Five portfolios have a Citation Index value over two (i.e., they have

[14] The Citation Index 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 H01M 8 (Fuel Cell Manufacturing) 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.

been cited more than twice as frequently as expected). These portfolios are advanced batteries, bioenergy feedstocks, solid state lighting, wind energy, and solar photovoltaics.

EERE-funded patents have also had a notable influence on subsequent patents owned by the leading companies in their respective technologies. On average, 9.8% of leading companies' patent families in each technology are linked via citations to earlier EERE-funded patents. The range for this statistic is from 0.1% to 30.7%, with several EERE-funded portfolios being linked to more than 20% of the patent families owned by the leading companies in their technology.

As such, although EERE-funded patents only represent a small percentage of the total patent universe across the twenty technologies (as noted above), they have been cited much more frequently than expected, including by leading companies in their respective technologies. This demonstrates that they have had a strong influence on subsequent technological developments.

Table 4 contains examples of individual highly-cited EERE-funded patents, with one patent selected from each of the twenty portfolios. These patents are defined as highly-cited based on their Citation Index value, with values above one again denoting patents that have been cited as prior art by more subsequent patents than expected. For example, Table 4 contains a 2014 patent in the HVAC portfolio (US #8,769,971) that is assigned to the Alliance for Sustainable Energy, through its management of NREL. This patent describes an indirect evaporative cooler for use in air conditioning systems. It has been cited as prior art by thirty-seven subsequent U.S. patents, which is over thirteen times as many citations as expected for a patent of its age and technology (i.e., the expected number of citations would only be around three).

Table 4 also contains a much older EERE-funded fuel cells patent (US #6,013,385) assigned to Emprise Corporation. This patent, which was issued in 2000, has been cited as prior art by 223 subsequent patents, more than seven times as many citations as expected (i.e., one would expect around thirty citations for a patent of this age and technology). One advantage of using the Citation Index metric is that patents of different ages and technologies can be compared, since the metric is normalized to take these characteristics into account, whereas raw citation counts can sometimes be misleading.

Table 4 – Examples of Highly Cited EERE-funded Patents (one from each EERE portfolio)

Portfolio	Patent #	Issue Year	# Cites	Citation Index	Assignee	Title
Additive Mfg	7967570	2011	8	1.21	United Technologies	Low transient thermal stress turbine engine components
Algae	5661017	1997	88	3.17	MRI Global (NREL)	Method to transform algae, materials therefor, and products produced thereby
Bioenergy Conversion	7425657	2008	132	26.24	Battelle Mem Inst (PNNL)	Palladium catalyzed hydrogenation of bio-oils and organic compounds
Bioenergy Feedstocks	6022419	2000	113	4.27	MRIGlobal (NREL)	Hydrolysis and fractionation of lignocellulosic biomass
HVAC	8769971	2014	37	13.51	Alliance Sustain Energy (NREL)	Indirect evaporative cooler using membrane-contained, liquid desiccant for dehumidification
Appliances	5521360	1996	105	5.41	Lockheed Martin (ORNL)	Apparatus and method for microwave processing of materials
Water Heating	5687706	1997	47	2.85	Univ Florida	Phase change material storage heater
Fuel Cells	6013385	2000	223	7.23	Emprise Corp	Fuel cell gas management system
Hydrogen Production	7618606	2009	98	13.79	Ohio State Univ	Separation of carbon dioxide (CO2) from gas mixtures by calcium based reaction separation (CaRS-CO2) process
Hydrogen Storage	6746496	2004	58	3.07	Sandia Corp	Compact solid source of hydrogen gas
Geothermal	6986251	2006	62	4.50	UTC Power	Organic Rankine cycle system for use with a reciprocating engine
Marine Hydrokinetics	9140231	2015	6	5.24	Sandia Corp (SNL)	Controller for a wave energy converter
Solar PV	7435897	2008	149	12.80	Schott Solar	Apparatus and method for mounting photovoltaic power generating systems on buildings
Concentrating Solar Power	7033570	2006	66	5.93	MRIGlobal / Univ Colorado	Solar-thermal fluid-wall reaction processing
Solid State Lighting	7821023	2010	124	13.90	Cree Inc	Solid state lighting component
Advanced Batteries	6677082	2004	117	9.05	Univ Chicago (ANL)	Lithium metal oxide electrodes for lithium cells and batteries
Advanced Combustion	7721543	2010	75	8.63	Southwest Res Inst	System and method for cooling a combustion gas charge
Propulsion Materials	7252054	2007	16	4.04	Caterpillar	Combustion engine including cam phase-shifting
Lightweight Materials	8061579	2011	13	4.78	UT-Battelle (ORNL)	Friction stir method for forming structures and materials
Wind Energy	7004724	2006	86	6.99	General Electric	Method and apparatus for wind turbine rotor load control based on shaft radial displacement

The Citation Index metric is based on a single generation of citations – i.e., the patents that reference a particular patent or set of patents as prior art. The citation analysis used in this report also includes a second generation of citations, in order to trace more extensively the influence of EERE-funded patents on subsequent innovations. Based on this two-generation tracing, Figure

11 shows the companies with the largest number of patent families that are linked via citations to earlier EERE-funded patents in the twenty portfolios. This figure contains many very large companies across a range of industries, including companies from the automotive, industrial, electronics and chemical sectors. As such, Figure 11 reflects the breadth of the influence of EERE-funded patents on subsequent innovations associated with many large companies that are household names.

Figure 11 - Companies with Largest Number of Patent Families Linked via Citations to EERE-funded Patents in Twenty Portfolios

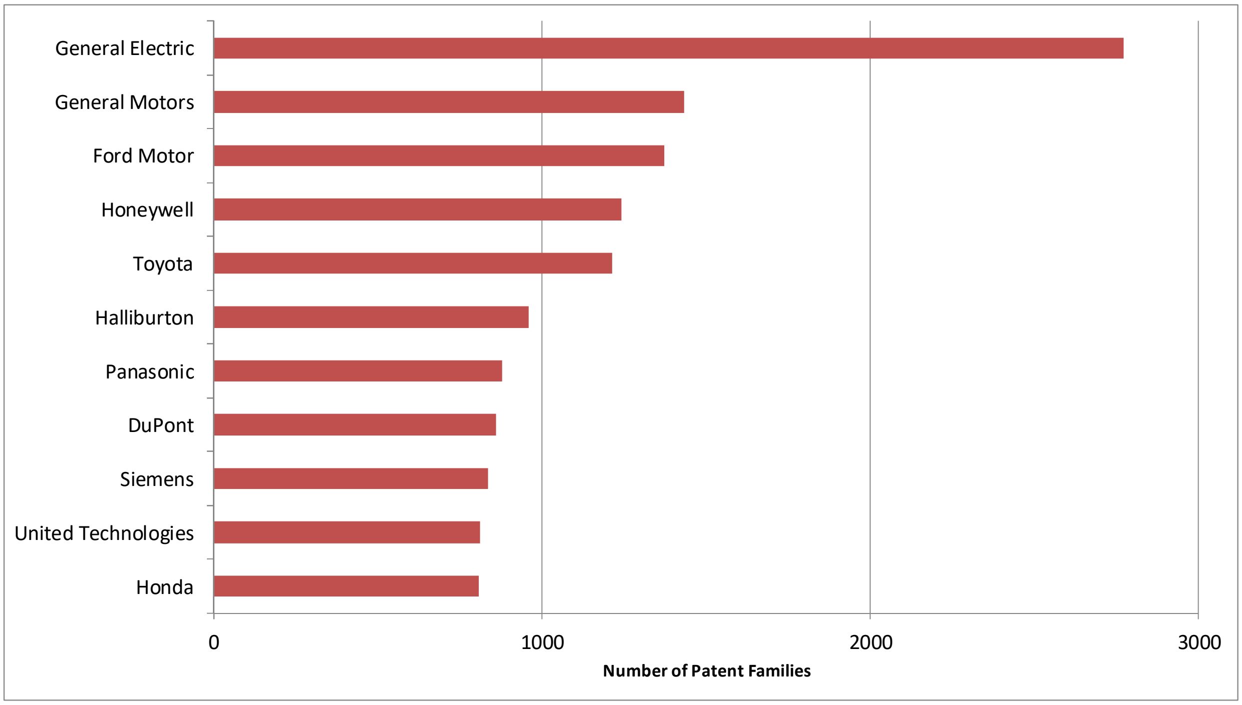


Figure 11 is based on companies with the highest numbers of patents linked via citations to all twenty EERE-funded portfolios combined. It is thus inevitably dominated by companies linked to the largest of these portfolios, since these portfolios have more patents available to be cited as prior art. Table 5 drills down to the level of individual EERE-funded portfolios. Specifically, this table shows which leading companies in each technology have the highest percentage of their patent families linked via citations to the corresponding EERE-funded portfolio.[15] These companies are listed in descending order according to this percentage. For example, in advanced batteries, Samsung SDI has the highest percentage of its battery patent families linked via citations to earlier EERE-funded battery patents, followed by Toshiba, LG Chem, Bosch, Sony and Panasonic in that order. Hence, EERE-funded battery research appears to have had a particularly strong influence on battery innovations associated with these companies..

[15] Note that some of the companies listed in Table 5 were themselves funded by EERE. In these cases, the citation links include links from the companies' later patents to their own earlier EERE-funded patents. This is to be expected, as companies develop successive generations of their technologies. That said, these links from companies to themselves only represent a small fraction of the total citation links to EERE-funded patents.

Table 5 – Leading Companies with Highest Percentage of Patent Families in Each Technology that are Linked via Citations to the Associated EERE-funded Patent Portfolio

EERE Portfolio	Leading Companies
Additive Manufacturing	General Electric
Algal Systems	Reliance (Aurora Algae); Heliae; DSM; Algenol; ExxonMobil
Bioenergy Conversion	DuPont; Xyleco; Novo Nordisk (Novozymes)
Bioenergy Feedstocks	DuPont; ENI; Xyleco; Stora Enso (Virdia)
HVAC	Honeywell; Johnson Controls; United Technologies; LG Electronics
Appliances	Whirlpool; Haier; LG Electronics
Water Heating	Paloma; Navien; United Technologies; A.O. Smith
Fuel Cells	Ballard Power; General Motors; Doosan; Samsung SDI; Honda
Hydrogen Production	Linde; Air Products & Chemicals; Chevron; Shell; Panasonic
Hydrogen Storage	Energy Conversion Devices; BASF; General Motors; Entegris; Intelligent Energy
Geothermal	Chevron; Halliburton; Ormat
Marine Hydrokinetics	Boeing (Liquid Robotics)
Solar PV	Total SA (SunPower)
Concentrating Solar Power	Boeing; Oscilla
Solid State Lighting	Cree; General Electric; Toshiba; Osram
Advanced Batteries	Samsung SDI; Toshiba; LG Chem; Bosch; Sony; Panasonic
Advanced Combustion	Caterpillar; Ford; General Motors
Propulsion Materials	Johnson Matthey; General Motors; Ford
Lightweight Materials	Mazda; Ford
Wind Energy	General Electric; Nordex; Senvion; Vestas; Mitsubishi Heavy

This analysis also examines the influence across technologies of the patents in the twenty EERE-funded portfolios. Figure 12 shows the most common CPCs among the patents linked – again via two generations of citations – to the twenty EERE portfolios. Not surprisingly, this figure is headed by CPC Y02E (Green Energy), which is a catch-all CPC for renewable energy technologies, as outlined earlier. Also prominent in Figure 12 are CPCs for Green Manufacturing (Y02P) and Green Transportation (Y02T), both of which were also among the leading CPCs for EERE-funded patents in Figure 8. One CPC in Figure 12 that did not feature in that earlier figure is Y02B, which is related to Green Buildings technology[16]. This CPC covers technologies including energy-efficient HVAC, appliances, and lighting; integration of renewable energy technologies such as solar and geothermal in buildings; and 'smart' technologies to help reduce energy consumption. The presence of this CPC in Figure 12 thus demonstrates that EERE-funded patents have influenced many subsequent innovations in green buildings technology.

[16] The full name of this CPC is "Climate change mitigation technologies related to buildings, e.g. housing, house appliances or related end-user applications".

Figure 12 – Most Common CPCs among U.S. Patents Linked via Citations to Earlier EERE-Funded Patents in Twenty Portfolios

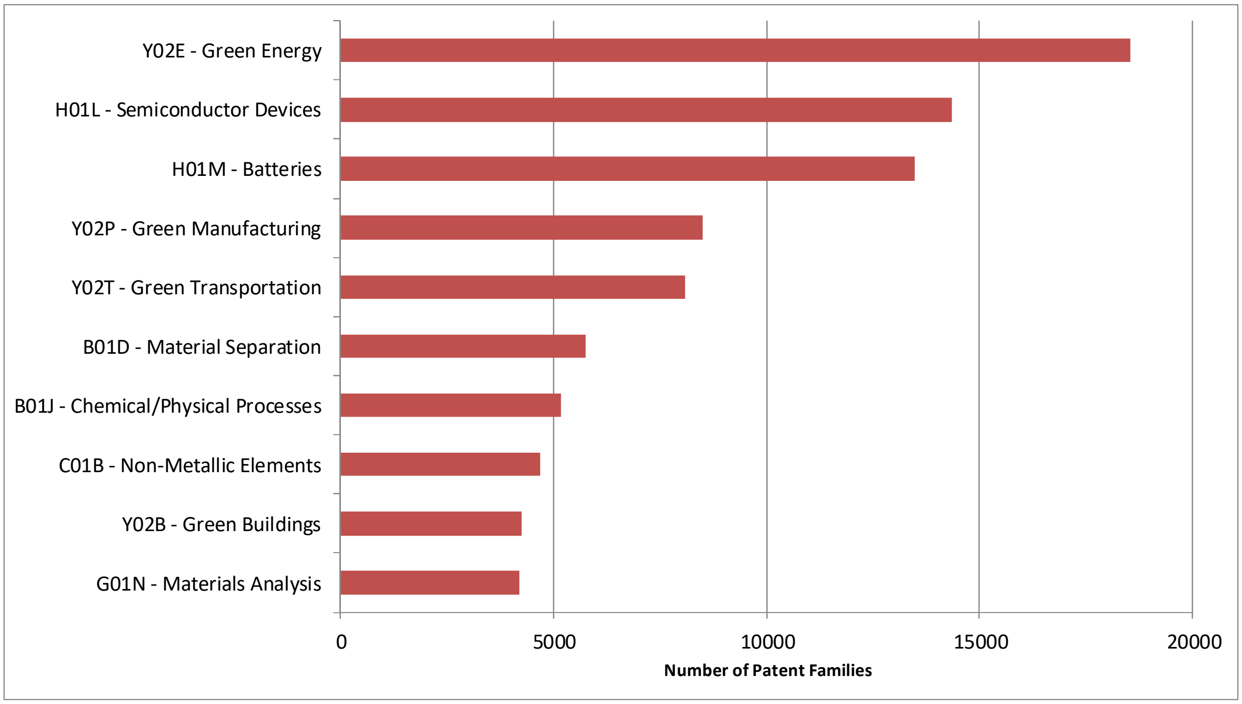


Figure 12 also contains a number of CPCs related to specific technologies. The most prominent of these are H01L (Semiconductor Devices) and H01M (Batteries). These CPCs were also near the head of Figure 8, which was based on EERE-funded patents. As such, this finding reflects the influence of EERE-funded patents on later generations of these technologies. Also present in both of these figures are CPCs for chemical and physical processes (B01J) and non-metallic elements (C01B). There are two new CPCs in Figure 12, which are related to Material Separation (B01D) and Materials Analysis (G01N). The former includes a wide range of technologies associated with fluid handling, while the latter is concerned with materials analysis using a variety of approaches, including optical, mechanical and thermal methods.

Table 6 examines the influence of each of the twenty portfolios individually. It lists the technologies where the influence of each portfolio can be detected (beyond the subject technology itself). It thus shows spillovers from each portfolio into other technologies. Some of these spillovers are into technologies adjacent to the subject portfolio, for example fuel cells in the case of advanced batteries, or hydropower in the case of marine hydrokinetics. Other spillovers are into technologies that are not generally regarded as adjacent to the subject portfolio, for example semiconductor manufacturing in the cases of the water heating and lightweight materials portfolios, or chemical detection in the case of advanced combustion.

Table 6 – Examples of Technology Spillovers from Each of the Twenty EERE Portfolios

EERE Portfolio	Spillover Technologies
Additive Manufacturing*	electronics; semiconductors; advanced materials; medical devices
Algal Systems	waste water treatment; power generation; carbon dioxide sequestration
Bioenergy Conversion	chemical production; materials processing
Bioenergy Feedstocks	chemical manufacturing; waste treatment
HVAC	advanced materials; solar thermal energy; semiconductor manufacturing
Appliances	nanocomposites; advanced materials; energy storage
Water Heating	electronics and semiconductor manufacturing; gas turbines; solar energy
Fuel Cells	advanced batteries; nanomaterials
Hydrogen Production	waste gas treatment; bioenergy
Hydrogen Storage	nanocomposites; advanced materials
Geothermal	energy storage; material handling; waste water treatment
Marine Hydrokinetics	wind energy; hydropower
Solar PV	semiconductors; nanomaterials; optics and displays
Concentrating Solar Power	photovoltaics; material science; bioenergy; optics
Solid State Lighting	semiconductors; electronics; advanced materials
Advanced Batteries	fuel cells; nanocomposites; imaging systems
Advanced Combustion	chemical detection and measurement
Propulsion Materials	earth drilling; brazing; advanced materials (non-vehicle)
Lightweight Materials	semiconductors; advanced materials (non-vehicle)
Wind Energy	power grid management; electrical generators and motors (non-wind)

* In Additive Manufacturing, these spillovers are largely from the overall DOE patent portfolio, rather than the much smaller and more recent AMO portfolio

Table 7 drills down into each portfolio and identifies individual patents that are linked via citations to large numbers of subsequent patent families from outside the subject technology. These subsequent patent families are referred to as “spillover families” in the right-hand column of Table 7. For example, EERE-funded hydrogen production patent family number 23799772 (which has the representative patent number US #4,473,622) is linked via citations to 924 subsequent patent families from outside hydrogen production. These include families in adjacent technologies such as fuel cells (especially for vehicle applications), and also families in other technologies such as carbon dioxide sequestration and hydrocarbon extraction. Similarly, EERE-funded geothermal patent family number 22804569 (which has the representative patent number US #4,389,071) is linked via citations to 901 subsequent patent families from outside geothermal technology. Again, these include families in adjacent technologies such as drilling and exploration, and other technologies such as fluid handling, for example atomizers and nebulizers used in medical applications.

Table 7 – EERE-funded Patent Families (one from each portfolio) Linked via Citations to Large Numbers of Subsequent Patent Families from Outside Subject Technology

Portfolio	Family #	Priority Year	Patent #	Assignee	Title	No. Spillover Families
Additive Mfg	49715918	2012	8951303	UT-Battelle (ORNL)	Freeform fluidics	1
Algae	25521521	1978	4253271	Battelle Mem Inst (PNNL)	Mass algal culture system	274
Bioenergy Conversion	25514461	1992	5504259	MRIGlobal (NREL)	Process to convert biomass and refuse derived fuel	178
Bioenergy Feedstocks	22426685	1993	5424417	MRIGlobal (NREL)	Prehydrolysis of lignocellulose	518
HVAC	24881021	2000	6711470	Bechtel BWXT Idaho (INL)	Method and system for monitoring/adjusting the quality of indoor air	240
Appliances	23184715	1994	5521360	Lockheed Martin (ORNL)	Apparatus and method for microwave processing of materials	590
Water Heating	23700908	1995	5687706	Univ Florida	Phase change material storage heater	353
Fuel Cells	25339073	1992	5316871	General Motors	Membrane-electrode assemblies for electrochemical cells	490
Hydrogen Production	23799772	1982	4473622	General Electric	Rapid starting methanol reactor system	924
Hydrogen Storage	24508779	1996	6015041	Westinghouse Savannah Riv (SRNL)	Apparatus and methods for storing and releasing hydrogen	345
Geothermal	22804569	1980	4389071	Hydronautics	Enhancing liquid jet erosion	901
Marine Hydrokinetics	38821135	2006	7489046	Northern Power Syst	Water turbine system and method of operation	55
Solar PV	23367734	1989	5053083	Stanford Univ	Bilevel contact solar cells	352
Concentrated Solar Power	22522277	1993	5417052	MRIGlobal (NREL)	Hybrid solar central receiver for power plant	256
Solid State Lighting	35197575	2004	7286296	Light Prescriptions Innovators	Optical manifold for light-emitting diodes	212
Advanced Batteries	27025104	1989	5162175	Univ California (LBNL)	Cell for making secondary batteries	664
Advanced Combustion	24809071	1996	5711147	Univ California (LLNL)	Plasma-assisted catalytic reduction system	472
Propulsion Materials	23767187	1995	5744075	Lockheed Martin (ORNL)	Method for rapid fabrication of fiber preforms	220
Lightweight Materials	23586345	1995	5458927	General Motors	Process for formation of wear and scuff resistant carbon coatings	536
Wind Energy	24003638	1995	5798632	MRIGlobal (NREL)	Variable speed wind turbine generator	367

4.0 Conclusions

This report provides a synthesis of a series of recent analyses conducted for the Department of Energy (DOE) Office of Energy Efficiency & Renewable Energy (EERE). The objective of these analyses is to trace the influence of research funded by various offices within EERE. The analyses cover a total of twenty different research portfolios across nine EERE offices.

The report shows that EERE-funded patenting across the twenty portfolios has increased over time, with the bulk of EERE-funded patents concentrated in the most recent time periods from 2010 onwards. Also, while EERE-funded patents only represent a small percentage of the total patent universe across the twenty technology areas (0.6% overall), they have been cited 67% more frequently by subsequent patents than expected. EERE-funded patents in the twenty portfolios are also linked via citations to an average of almost 10% of leading company patent families in their respective technologies.

This report thus demonstrates that EERE-funded patents have had a strong influence on subsequent technological developments. This influence can be seen on innovations associated with many very large companies from across the energy, automotive, industrial, electronics and chemical sectors. The influence of EERE-funded patents can also be seen across patent classifications related to applications of renewable energy in transportation, manufacturing, energy, and building technologies.

Appendix A. List of Patent Studies for the Twenty EERE R&D Portfolios

(Individual reports can be found at https://www.energy.gov/eere/analysis/eere-evaluation-publications)

The Influence of Solar Photovoltaics Patents Funded by the U.S. Department of Energy's Solar Energy Technologies Office and other DOE Offices
The Influence of Concentrating Solar Power Patents Funded by the U.S. Department of Energy's Solar Energy Technologies Office and other DOE Offices
The Influence of Wind Energy Patents Funded by the U.S. Department of Energy's Wind Energy Technologies Office and other DOE Offices
The Influence of Geothermal Patents Funded by the U.S. Department of Energy's Geothermal Energy Technologies Office and other DOE Offices
The Influence of Marine and Hydro Kinetics Patents Funded by the U.S. Department of Energy's Water Power Technologies Office and other DOE Offices
The Influence of Advanced Combustion Engine Patents Funded by the U.S. Department of Energy's Vehicle Technologies Office and other DOE Offices
The Influence of Advanced Battery Patents Funded by the U.S. Department of Energy's Vehicle Technologies Office and other DOE Offices
The Influence of Lightweight and Propulsion Materials Patents Funded by the U.S. Department of Energy's Vehicle Technologies Office and other DOE Offices
The Influence of Fuel Cell, Hydrogen Production, and Hydrogen Storage Patents Funded by the U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office and Other DOE Offices
The Influence of Bioenergy Conversion Patents Funded by the U.S. Department of Energy's Bioenergy Technologies Office and other DOE Offices
The Influence of Algae Patents Funded by the U.S. Department of Energy's Bioenergy Technologies Office and other DOE Offices
The Influence of Feedstock Patents Funded by the U.S. Department of Energy's Bioenergy Technologies Office and other DOE Offices
The Influence of Additive Manufacturing Patents Funded by the U.S. Department of

Appendix B. Defining Portfolios of EERE-funded Patents

As noted in the body of the report, the process used to define each of the twenty portfolios of EERE-funded patents consisted of four distinct steps:

Step 1: Define the universe of DOE-funded U.S. patents;

Step 2: Select the patents in this DOE patent universe (from Step 1) that are relevant to the subject technology (using a patent filter consisting of keywords and patent classifications);

Step 3: Determine which of the technology-relevant DOE-funded patents (from Step 2) were funded by the EERE office in question; and

Step 4: Take the list of technology-relevant EERE-funded patents (from Step 3), and add to this list other members of the patent families to which these EERE-funded patents belong.

The output of this four-step process is a list of EERE-funded U.S., EPO, and WIPO patents in each of the twenty portfolios, grouped according to their patent family. Details of each of the four steps are provided below.

Step 1: Define 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 Laboratories are assigned to Lockheed Martin (Sandia's former M&O contractor), 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.

It was therefore necessary to construct a database containing all DOE-funded patents. These include patents assigned to DOE itself, and also patents assigned to individual labs, their M&O contractors, 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 supplied 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 supplied an output from its Visual Patent Finder tool. This tool takes DOE-funded patents and clusters them based on word occurrence patterns. In this case, the output was a file containing DOE-funded patents.

4. ***Patents Assigned to DOE*** – in the USPTO database, there are a small number of U.S. patents assigned to DOE itself that were not in 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 company, the government may have certain rights to patents granted based on this research. All patents that refer to 'Department of Energy' or 'DOE' in their Government Interest field, (including different variants of these strings) were therefore identified. Also identified were 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. Patents containing these strings that were not already in any of the sources above were then checked manually, to make sure that they are indeed DOE-funded (e.g., '-ENG-' is also used in a small number of NSF contracts). Any additional DOE funded patents were then included 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).

Step 2: Select DOE-funded Patents Relevant to the Subject Technology

Having defined the universe of DOE-funded patents, the next step is to determine which of these patents are relevant to a given subject technology – for example advanced combustion, concentrating solar power, or domestic appliances. For each portfolio, a custom patent filter was used to identify relevant DOE-funded patents, consisting of a combination of Cooperative Patent Classifications (CPCs) and keywords. These filters were often augmented by specific technological terms suggested by the associated EERE office. Also, in some cases, these offices supplied lists of patents that they had funded in the relevant technology.

Step 3: Determine which Technology-Relevant Patents were funded by EERE

The output from Step 2 is a list of DOE-funded patents relevant to each subject technology. The next step is to determine which of these patents were funded by EERE. 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 DOE-funded patents from Step 2 could be linked definitively to funding from the associated EERE office. 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 EERE technology managers to verify individual patents,
(iv) Asking EERE technology managers to send lab patents to lab POCs to get direct verification of these patents,
(v) Contacting individual inventors listed on patents to ask them to confirm whether individual patents were funded by a given EERE office, and
(vi) Locating references to patents in available office annual project progress reports or patent disclosure documents with accomplishments reported by PIs.

Step 4: Add Patent Family Members Associated with EERE-funded Patents

Based on the process described above in Step 3, the DOE-funded patents in each technology are divided into two categories – EERE office-funded and Other DOE-funded. A search was then undertaken for other U.S., EPO and WIPO patents that are members of the same "patent families" as these initial patents.[17] These family members were added to the original patent lists.

The final output from this four-step process is a list of all identified U.S., EPO and WIPO patents in each of the twenty EERE-funded portfolios, with these patents grouped into patent families.

[17] The coverage of a patent is limited to the jurisdiction of its issuing authority. As an 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 instance, an organization 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. Also, in some systems – notably the U.S. – inventors may apply for a series of patents based on one underlying invention. To identify all patents related to an invention (and avoid double counting these patents), it is necessary to construct "patent families". A patent family contains all patents resulting from the same initial application (named the priority application). In the case of this study, each patent family may contain multiple U.S., EPO and WIPO patents. It should be noted that the priority document for these families need not necessarily be a U.S., EPO or WIPO application. For example, a Japanese patent application may result in U.S., EPO and WIPO patents, which are grouped in the same patent family because they share the same Japanese priority document.

Appendix C. Details of Influence Tracing Methodology

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.

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, citations from patents to earlier patents are used to trace the influence of EERE-funded research. Specifically, cases are identified where patents cite EERE-funded patents as prior art. These represent first-generation links between EERE-funded patents and subsequent technological developments. Cases are also identified where patents cite patents that in turn cite EERE-funded patents. These represent second-generation links between innovations and EERE-funded research. The idea behind this analysis is that the later patents build in some way on the earlier EERE-funded research. By determining how frequently EERE-funded patents have been cited by subsequent patents, it is thus possible to evaluate the extent to which EERE-funded research forms a foundation for various later innovations.

Forward and Backward Tracing

As noted above, the purpose of this analysis is to trace the influence of EERE-funded research portfolios upon subsequent developments both within and their immediate technology. There are two approaches to such a tracing study – forward tracing and backward tracing – each of which has a slightly different objective.

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 patents in each EERE-funded portfolio. The influence of these patents on later generations of technology is then evaluated. This tracing is not restricted to subsequent patents from the technology associated with each portfolio, 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 EERE-funded patents upon developments both inside and outside their associated technology.

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, the leading organizations in a given technology (in terms of patent portfolio size) are identified, and a tracing is carried out backwards in time from the patents owned by these organizations. This makes it possible to determine the extent to which innovations associated with these leading organizations build on earlier EERE-funded research.

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.

The forward tracing starts with EERE-funded patents in each portfolio. The first generation contains the patents that cite these EERE-funded patents as prior art. The second generation contains the patents that in turn cite these first-generation patents. Hence, the analysis starts with EERE-funded patents and traces forwards in time for two generations of subsequent patents.

The backward tracing starts with patents assigned to the leading patenting organizations in each subject technology. The first generation contains the patents that are cited as prior art by these starting patents, while the second generation contains patents that are in turn cited by these first generation patents. The backward tracing thus starts with patents owned by leading organizations in each technology, and traces backwards in time through two generations of citations to identify the technologies upon which they were built, including those funded by EERE.

The idea behind adding the second generation of citations is that government agencies 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.

An Analysis of the Influence of EERE-funded Patents

Report prepared by 1790 Analytics LLC

DOE/EERE Publication Number: 2567