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

The main finding of this report is:

- Wind energy research funded by WETO, and by DOE in general, has had a significant influence on subsequent developments, both within and beyond wind energy technology. This influence can be seen upon innovations associated with the leading wind energy companies. It can also be traced in other technologies, notably power distribution and electrical generators and motors.

More detailed findings from this report include:

- In wind energy technology, in the period 1976-2018, we identified a total of 32,977 patents (9,649 U.S. patents, 11,160 EPO patents and 12,168 WIPO patents). We grouped these patents into 22,191 patent families, where each family contains all patents resulting from the same initial application (named the priority application).

- 174 wind energy patents are confirmed to be associated with WETO funding (114 U.S. patents, 36 EPO patents, and 24 WIPO patents). We grouped these WETO-funded wind energy patents into 98 patent families.

- In addition, we identified a further 62 wind energy patents (39 U.S. patents, 13 EPO patents and 10 WIPO patents) that are associated with DOE funding. These "Other DOE-funded" patents are grouped into 32 patent families.

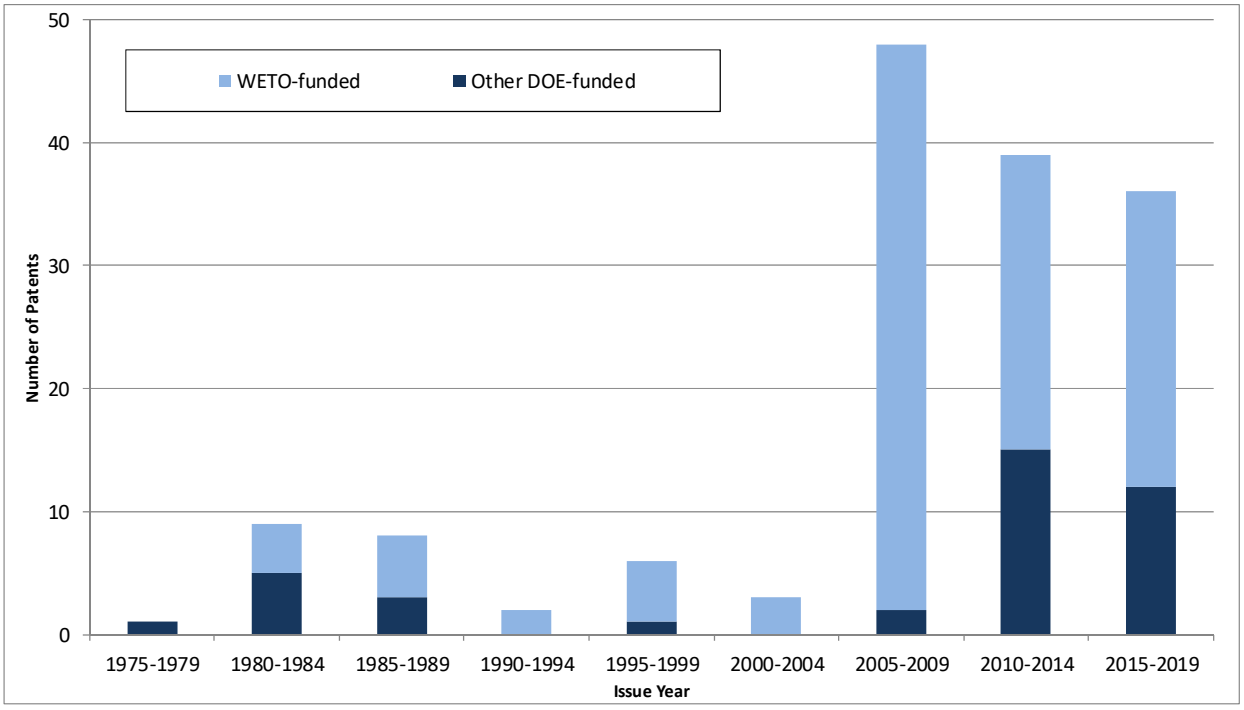
- Out of these 32 Other DOE-funded patent families, 21 are definitely not WETO-funded. These patent families were either funded by a different DOE office, or were marked as being not WETO-funded by inventors or WETO technology managers, but without specifying funding from another DOE source.

- The remaining 11 Other DOE-funded wind energy patent families could not be linked definitively to a specific DOE funding source, and may in fact have been WETO-funded. Hence, up to 34% (11 out of 32) of the Other DOE-funded wind energy patent families in this analysis may in fact be WETO-funded. As such, the results presented in this report may understate the influence of WETO-funded wind energy research, relative to the influence of wind energy research funded by DOE in general.

- The total number of DOE-funded wind energy patents (WETO-funded plus Other DOE-funded) is 236, corresponding to 130 patent families. This represents 0.6% of the total number of wind energy patent families in the period 1976-2018.

- Figure E-1 shows the number of WETO-funded and Other DOE-funded wind energy U.S. patents by issue year. This figure reveals that DOE-funded wind energy patenting was relatively sparse in the earlier time periods in the analysis. The number of DOE-funded U.S. patents increased sharply in 2005-2009, with 48 patents issued (all but two of which were WETO-funded). DOE-funded patents then fell to 39 in 2010-2014 (24 WETO-funded), before falling further to 36 (24 WETO-funded) in 2015-2019, although data for the latter time period are incomplete (see note below Figure E-1).

Figure E-1 - Number of WETO/Other DOE-funded Wind 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.

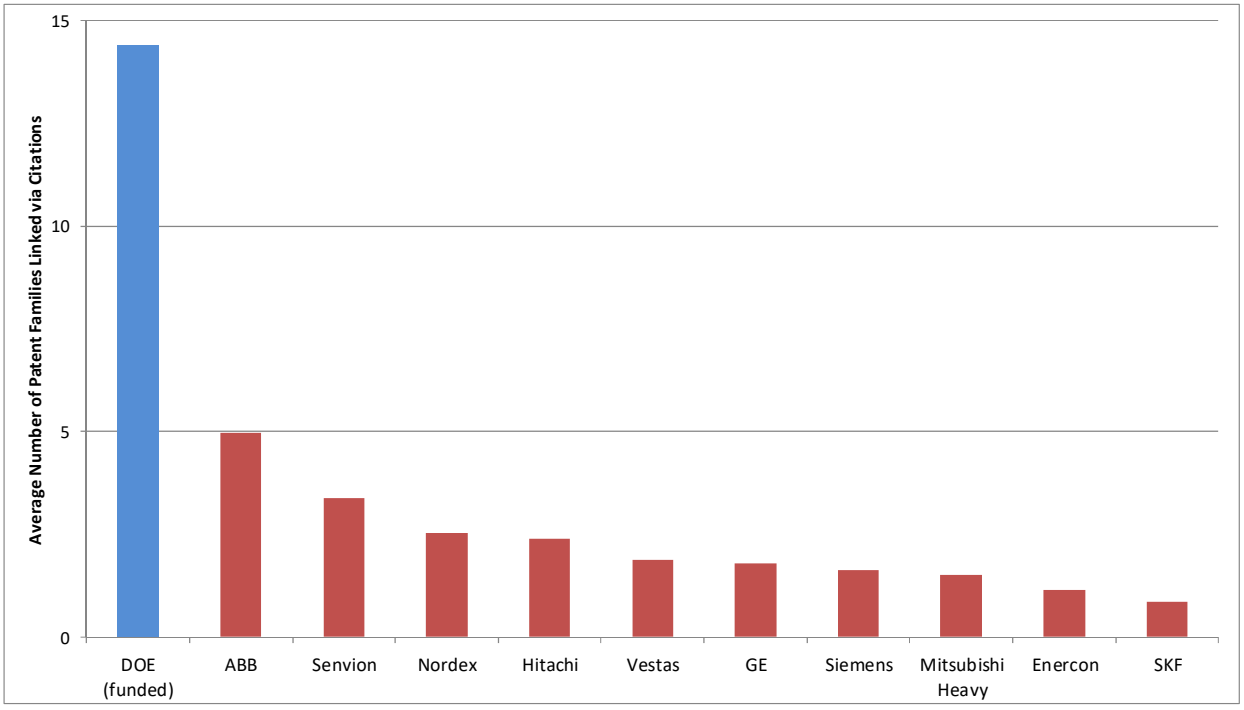
- The ten companies with the largest wind energy patent portfolios are: General Electric (2157 patent families); Vestas Wind Systems (1699); Siemens (1680); Mitsubishi Heavy Industries (744); Senvion (362); Enercon (350); Nordex (282); Hitachi (238); ABB (170);

and SKF (127). In comparison, the portfolio of 130 DOE-funded wind energy patents (98 WETO-funded and 32 Other DOE-funded) is relatively small. This size difference is taken into account in assessing the influence of the various patent portfolios.

- WETO-funded patents have a particular focus on wind turbine control systems, generators, blades and nacelles. The leading companies, and wind energy patents overall, have a notable presence across these technologies, with the exception of nacelles, where they have a lower percentage of patents. This suggests that, in the period 1976-2018, WETO funding helped to fill a research gap related to nacelle technology. Meanwhile, Other DOE-funded patents are focused mainly on wind turbine blades and control systems.

- On average, DOE-funded wind energy patent families (most of which are WETO-funded) are each linked via citations to over fourteen subsequent patent families assigned to the leading wind energy companies (see Figure E-2). This means that, on average, more wind energy patent families owned by leading companies are linked via citations to earlier DOE-funded wind energy patents than are linked to the wind energy patents assigned to any other leading company. This is an impressive result and suggests that, while the portfolio of DOE-funded wind energy patents is relatively small, it has formed an important part of the foundation for innovations developed by the leading companies.

Figure E-2 - Average Number of Leading Company Wind Energy Patent Families Linked via Citations to Wind Energy Families from Each Leading Company
e.g. on average, each DOE-funded patent family is linked to fourteen subsequent patent families assigned to leading companies

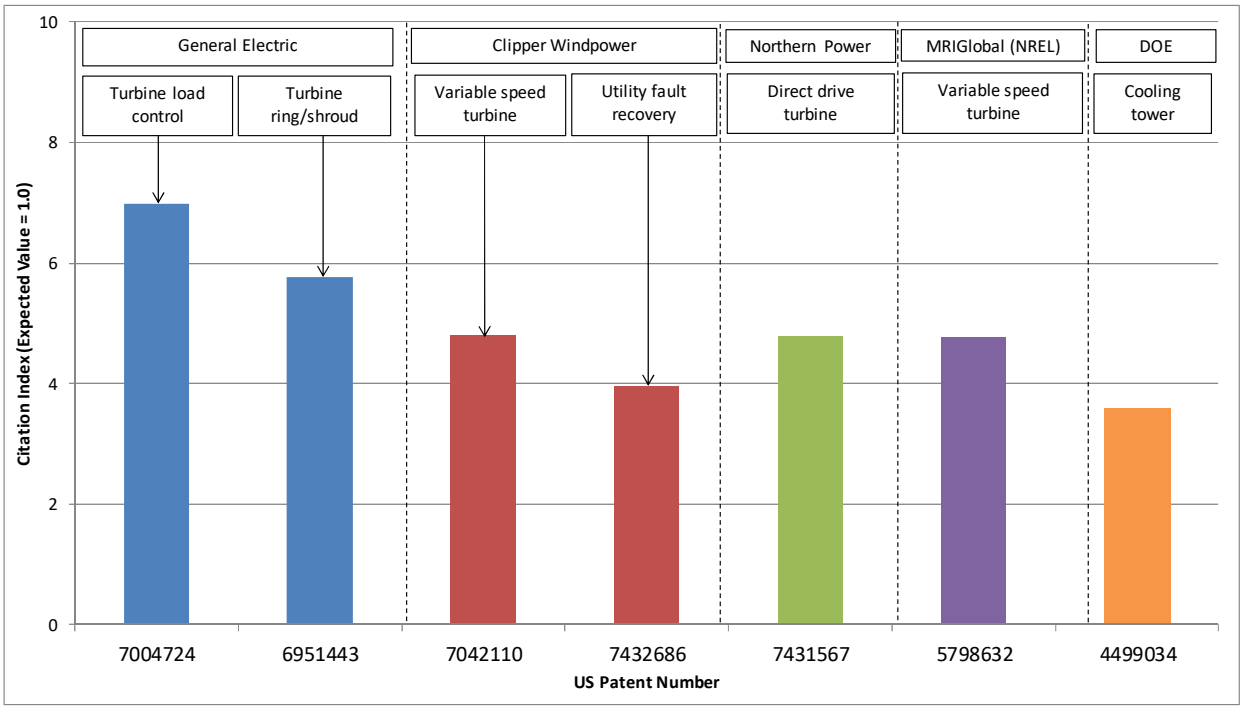


- Over one-third of General Electric's wind energy patent families are linked via citations to earlier WETO-funded wind energy patents. Senvion, Nordex and Vestas also have extensive citation links to WETO-funded patents. This suggests that WETO-funded research has had a particularly strong influence on innovations from these companies.

- WETO-funded wind energy patents have an average Citation Index value of 2.08 (the Citation Index is a normalized citation metric with an expected value of 1.0; a value of 2.08 shows that, based on their age and technology, WETO-funded wind energy patents have been cited as prior art more than twice as frequently as expected by subsequent patents). The Citation Index for Other DOE-funded wind energy patents is lower at 1.45, but this still means that these patents have been cited 45% more frequently than expected. The influence of WETO-funded and Other DOE-funded wind energy patents has been primarily within wind energy technology, but can also be traced in in adjacent technologies such as power distribution and electrical generators and motors.

- There are a number of individual high-impact WETO-funded wind energy patents, examples of which are shown in Figure E-3. They include General Electric patents for turbine control and rings/shrouds, Clipper and MRIGlobal (NREL) patents for variable speed turbines, Northern Power patents for direct drive turbines, and an early DOE patent describing wind-powered cooling towers.

Figure E-3 – Examples of Highly-Cited WETO-funded Wind Energy Patents



1.0 Introduction

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

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

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

The primary focus of the report is on the influence of WETO-funded wind energy patents. That said, we also extend many elements of the analysis to DOE-funded wind energy patents that could not be definitively linked to WETO 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 WETO itself upon the development of wind energy technology, while also tracing the influence of DOE more generally. Meanwhile, in practical terms, determining which patents were funded by WETO, 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 WETO-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 WETO, although a definitive link could not be established. Hence, the results reported here may underestimate the influence of WETO-funded wind energy research, relative to the influence of wind 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 WETO-funded and Other DOE-funded patents. These results show the distribution of WETO-funded (and Other DOE-funded) patents across wind energy technologies (as defined by Cooperative Patent Classifications). They also evaluate the extent of WETO's influence (and DOE's influence in general) on subsequent developments in wind energy and other technologies. Patent level results are then presented to highlight individual WETO-funded wind energy patents that have been particularly influential, as well as to reveal key patents from other organizations that build extensively on WETO-funded wind 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 wind energy industry have used WETO-funded research as a foundation. Meanwhile, the primary purpose of the forward tracing is to examine how WETO-funded wind energy patents influenced subsequent technological developments more broadly, both within and outside wind energy 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 wind 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 possible linkages between DOE-funded wind energy research and subsequent technological developments. 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.

[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 WETO-funded wind energy patents and Other DOE-funded wind energy patents. However, referring repeatedly to "WETO-funded/Other DOE-funded patents" or "WETO-funded/Other DOE-funded research" in describing the analyses is lengthy, so we 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 wind energy research. Specifically, we identify cases where patents cite DOE-funded wind 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 wind energy patents.

[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.

These represent second-generation links between innovations and DOE-funded research. The idea behind this analysis is that the later patents build in some way on the earlier DOE-funded wind energy research. By determining how frequently DOE-funded wind 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 wind energy.

Forward and Backward Tracing

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

This means that we trace forward through two generations of citations starting from DOE-funded wind energy patents; and backward through two generations starting from the patents owned by leading wind 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 wind energy patent as prior art.
2. **Indirect Links**: where a patent cites an earlier patent, which in turn cites a DOE-funded wind energy patent. The DOE patent is thus 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 wind energy patents, and also for the patents owned by leading wind energy organizations. We also assembled families for all patents linked via citations to DOE-funded wind 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 result in U.S., EPO

[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.

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
• Number of WETO/Other DOE-funded wind energy patent families by year of priority application
• Number of WETO/Other DOE-funded granted U.S. wind energy patents by issue year
• Overall number of wind energy patent families by priority year
• Percentage of wind energy patents families funded by WETO/Other DOE by priority year
Assignee Metrics
• Number of wind energy patent families for leading patenting organizations
• Assignees with largest number of wind energy patent families funded by WETO/Other DOE
Technology Metrics
• Patent classification (CPC) distribution for WETO-funded wind energy patent families (vs Other DOE-funded, leading wind energy companies, all wind energy)
Backward Tracing Metrics
• Total/Average number of leading company wind energy patent families linked via citations to earlier patent families from WETO/Other DOE-funding and other leading companies
• Number of wind energy patent families for each leading company linked via citations to earlier WETO/Other DOE-funded patent families
• Total citation links from each leading company to WETO/Other DOE-funded patent families
• Percentage of leading company wind energy patent families linked via citations to earlier WETO/Other DOE-funded patent families
• WETO/Other DOE-funded wind energy patent families linked via citations to largest number of leading company wind energy patent families
• Leading company wind energy patent families linked via citations to largest number of WETO-funded wind energy patent families
• Highly cited leading company wind energy patent families linked via citations to earlier WETO-funded wind energy patent families
Forward Tracing Metrics
• Citation Index for wind energy patent portfolios owned by leading companies, plus portfolios of WETO/Other DOE-funded wind energy patents
• Number of patent families linked via citations to WETO/Other DOE-funded wind energy patents by patent classification
• Organizations (beyond leading wind energy companies) linked via citations to largest number of WETO/Other DOE-funded wind energy patent families
• Highly cited WETO-funded wind energy U.S. patents
• WETO/Other DOE-funded wind energy patent families linked via citations to largest number of subsequent wind energy/non-wind energy patent families
• Highly cited patents (not leading company-owned) linked via citations to WETO-funded wind energy patents

3.0 Methodology

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

Identifying WETO-funded and Other DOE-funded Wind Energy Patents

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

(iii) Categorizing these DOE-funded wind energy patents according to whether or not they can be linked definitively to WETO funding.

Defining the Universe of DOE-Funded Patents

Identifying patents funded by government agencies is often more difficult than locating patents funded by companies. When a company funds internal research, any patented inventions emerging from this research are likely to be assigned to the company itself. In order to construct a patent set for a company, one simply has to identify all patents assigned to the company, along with all of its subsidiaries, acquisitions, etc.

Constructing a patent list for a government agency is more complicated, because the agency may fund research carried out at many different organizations. For example, DOE operates seventeen national laboratories. Patents emerging from these laboratories may be assigned to DOE. However, they may also be assigned to the organization that manages a given laboratory. For example, many patents from Sandia National Laboratory are assigned to Lockheed Martin (Sandia's former lab manager), while many Lawrence Livermore National Laboratory patents are assigned to the University of California. Lockheed Martin and the University of California are large organizations with many interests beyond managing DOE labs, so one cannot simply 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 flat 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 Wind Energy Patents

Having defined the universe of DOE-funded patents, the next step was to determine which of these patents are relevant to wind energy technology. We designed a custom patent filter to identify wind 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), so patents that qualify under either of the filters in Table 2 were included in the initial patent set.

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

Filter A
Cooperative Patent Classification
F03D – Wind motors
Y02B 10/30 – Wind energy applications in buildings
Y02E 10/70-766 – Wind energy
Y02P 70/523 – Wind turbine manufacture
Y02P 80/22 – Wind energy applications in manufacturing
Filter B
Title/Abstract
HAWT or VAWT or (wind +/- 3 words (turbine* or energy* or power* or farm*))

We manually checked this initial list of patents to determine which of them appear relevant to wind energy, and then sent the resulting patent list to WETO for review. Following this review, and based on feedback from WETO, the initial list of wind energy patents funded by DOE contained a total of 147 granted U.S. patents.

Defining WETO-funded vs. Other DOE-funded wind 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 147 DOE-funded wind energy patents in the initial list could be linked definitively to WETO 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 WETO technology managers to verify individual patents,
(iv) Asking WETO 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 WETO, 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 WETO-funded and Other DOE-funded Wind Energy Patents

Based on the process described above, we divided the initial list of 147 DOE-funded wind energy U.S. patents into two categories – WETO-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 in the final set. 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 WETO-funded and Other DOE-funded wind energy patents and patent families.

Table 3 – Number of WETO-funded and Other DOE-funded Wind Energy Patents and Patent Families

	# Patent Families	# U.S. Patents	# EPO Patents	# WIPO Patents
WETO-funded	98	114	36	24
Other DOE-funded	32	39	13	10
Total DOE-funded	130	153	49	34

Table 3 shows that we identified a total of 98 WETO-funded wind energy patent families, containing 114 U.S. patents, 36 EPO patents, and 24 WIPO patents (see Appendix A for patent list). We also identified 32 Other DOE-funded wind energy patent families, containing 39 U.S. patents, 13 EPO patents, and 10 WIPO patents (see Appendix B for patent list). These DOE-funded portfolios date back to the mid-1970s, the starting point for this analysis

As noted throughout this report, the approach used to define patents as WETO-funded was very stringent. Hence, a number of the 32 Other DOE-funded patent families may in fact have been funded by WETO, 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 WETO-funded, we divided them into two groups.

The first group contains DOE-funded patent families that were definitely not funded by WETO. These include families linked specifically to funding from an office other than WETO, or that the inventor or WETO technology manager said were not funded by WETO (but without specifying funding from a different office). There are 21 such patent families.

The second group contains DOE-funded patent families where the funding source within DOE could not be established, and inventors and WETO technology managers could not state categorically whether or not they were funded by WETO. There are eleven such patent families. Hence, up to 34% (11 out of 32) of the Other DOE-funded patent families in this analysis may in fact be WETO-funded. The findings in this analysis may thus understate the influence of WETO-funded wind energy patents, relative to the influence of the remainder of DOE patents.

Identifying Wind Energy Patents Assigned to Leading Organizations

The backward tracing element of our analysis is designed to evaluate the influence of WETO-funded (and Other DOE-funded) research on wind energy innovations produced by leading

organizations in this technology. To identify such organizations, we first defined the universe of wind 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 9,649 wind energy U.S. patents, 11,160 wind energy EPO patents, and 12,168 wind energy WIPO patents. We grouped these patents into 22,191 patent families by matching priority documents.

We then located the most prolific patenting organizations in this overall wind energy patent universe, based on number of patent families. The ten organizations with the largest number of wind energy patent families are shown in Table 4.[6] 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. The wind energy patent families of these ten companies in Table 4 form the starting point for the backward tracing element of the analysis.

Table 4 – Top 10 Patenting Wind Energy Companies

Company	# Wind Energy Patent Families
General Electric	2157
Vestas Wind Systems	1699
Siemens	1680
Mitsubishi Heavy Industries	744
Senvion	362
Enercon	350
Nordex	282
Hitachi	238
ABB	170
SKF	127

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 wind energy technology. The patent sets for the forward tracing consisted of WETO-funded (and, separately, Other DOE-funded) wind energy patent families. We then traced backward through two generations of citations from the leading organizations' wind energy patents, and forward through two generations of citations from the WETO/Other DOE-funded wind 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.

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

4.0 Results

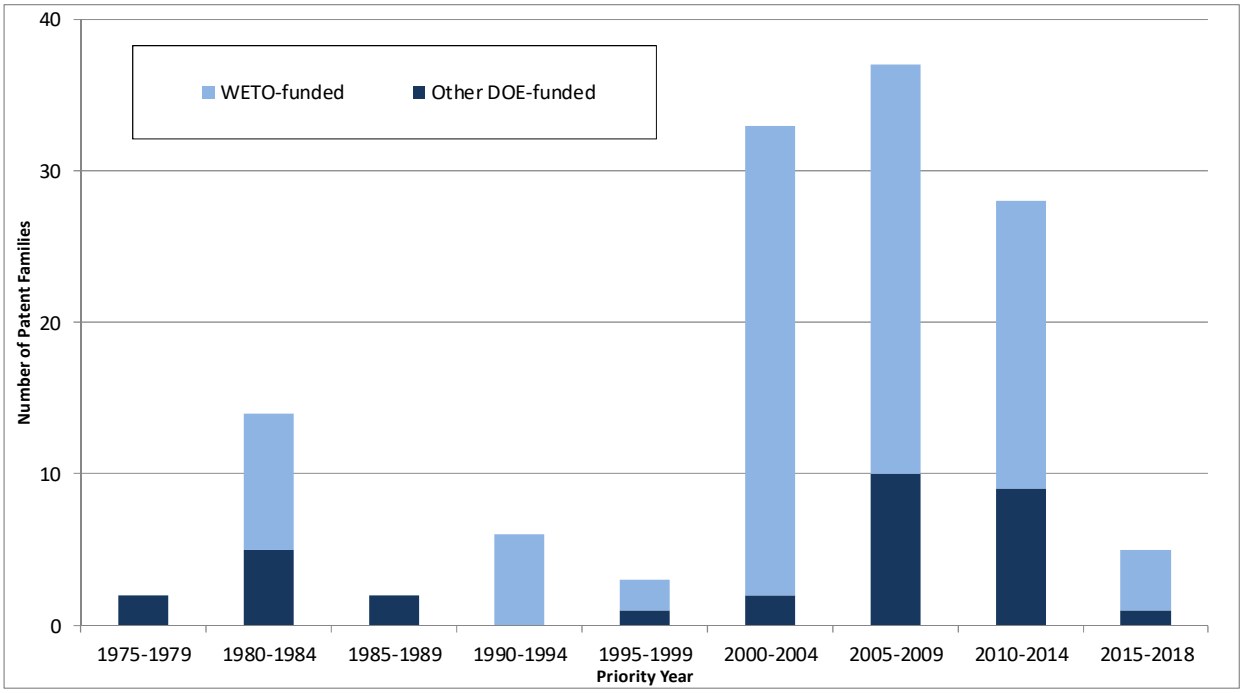
This section of the report outlines the results of our analysis tracing the influence of WETO-funded and Other DOE-funded wind energy research on subsequent developments both within and beyond wind energy technology. The results are divided into three main sections. In the first section, we examine trends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

Overall Trends in Wind Energy Patenting

Trends in Wind Energy Patenting over Time

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

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

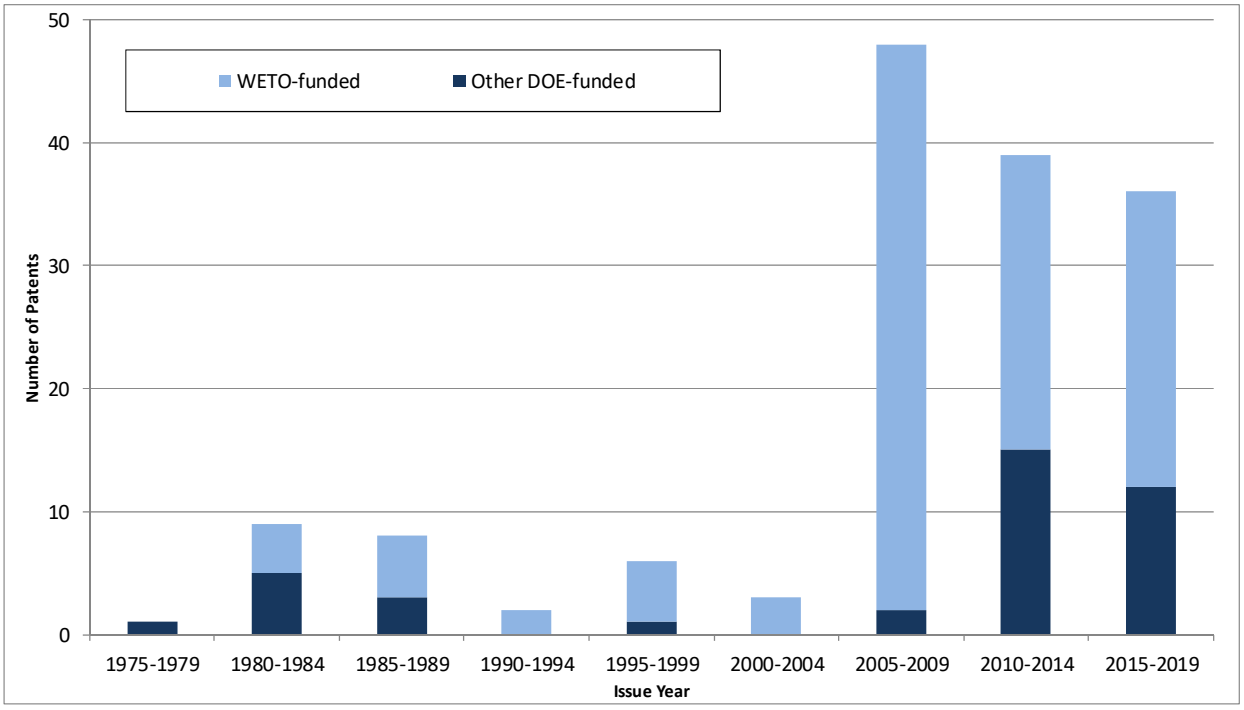


Note: The final time period in this figure is 2015-2018, and is shown for completeness, although data for this time period are incomplete. Our primary data collection covered only patents issued through 2018. Due to time lags associated with the patenting process, only a fraction of the patent families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

This figure reveals that DOE-funded wind energy patenting was relatively sparse in the earlier time periods in the analysis. Fewer than ten patent families were filed in each 5-year period through 1999, with the exception of 1980-1984 (14 patent families, nine of them WETO-funded). The number of DOE-funded patent families then increased sharply in 2000-2004, with 33 patent families filed (all but two of which were WETO-funded). DOE-funded families increased again to 37 in 2005-2009 (27 WETO-funded), before falling slightly to 28 (19 WETO-funded) in 2010-2014. The number of DOE-funded patent families fell again in 2015-2018, although data for this time period are incomplete (see note below Figure 1). Overall, there are 130 DOE-funded wind energy patent families, 98 of which are WETO-funded.

Figure 1 suggests that DOE-funded wind energy patenting is primarily focused in the period from 2000 onwards, with WETO-funding associated a high percentage of these patent families. This pattern is also reflected in Figure 2, which shows the number of wind energy granted U.S. patents funded by DOE in each time period. Here, DOE-funded U.S. patents were relatively sparse prior to 2005, before rising sharply to 48 in 2005-2009 (46 of which were WETO-funded). The number of DOE-funded U.S. patents fell to 39 in 2010-2014 (24 WETO-funded), and fell further to 36 in 2015-2019 (24 WETO-funded), although the decline in the latter period is partially explained by the incomplete data for this time period (see note below Figure 2).

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

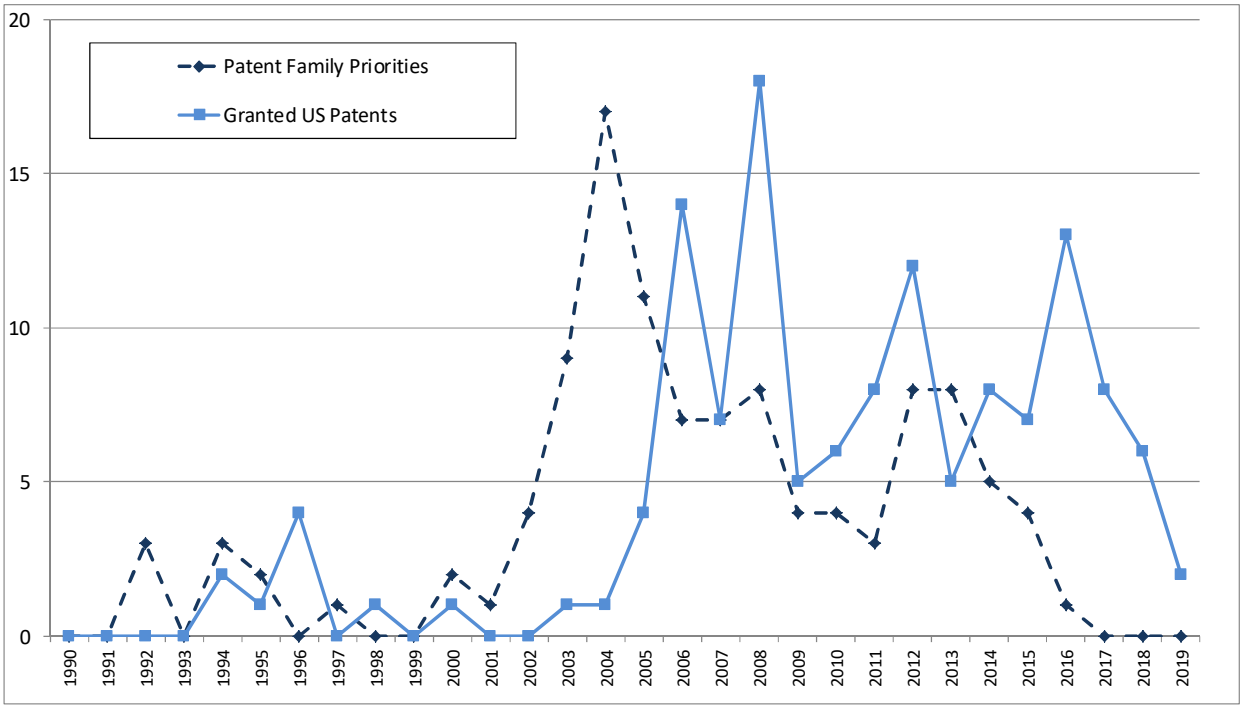


Note: The data collection period for this analysis ended with 2018. Any 2019 patents in the 2015-2019 column are additional patents that have been included because they are members of the same patent families as pre-2019 patents. No new patent search for 2019 was carried out.

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 wind energy patent family priority years alongside issue years for granted U.S. wind energy patents (in this figure, WETO and Other DOE are combined, in order to simplify the presentation). In this figure, the growth in patent families filed in 2002-2004 is associated with subsequent peaks in granted U.S. patents occurring in 2006 and 2008. More recently, patent family priorities dropped away after 2013, resulting in a decline in U.S. patents from 2016 onwards (note that, due to the primary data collection for this analysis ending in 2018, the number of granted U.S. patents declines sharply in 2019, and the number of families is zero).

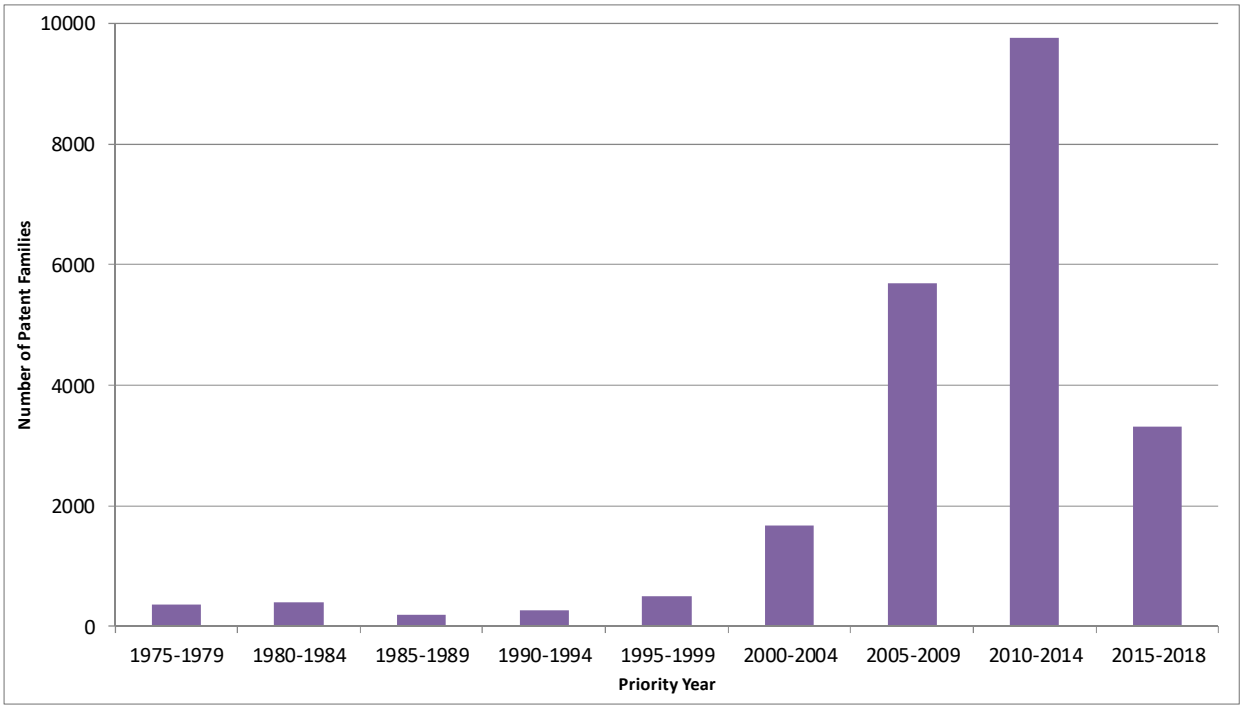
Figure 3 - Number of DOE-funded Wind Energy Patent Families (by Priority Year) and Granted U.S. Patents (by Issue Year)



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 wind energy patent families. Figure 4 broadens the scope, and shows the overall number of wind energy patent families by priority year (based on USPTO, EPO, and WIPO filings). This chart reveals that overall wind energy patenting was relatively low throughout the period from 1975 to 1999, averaging around 40-100 patent families per year (i.e. 200-500 families per 5-year period). The number of wind energy patent families then started to increase, to 1,673 in 2000-2004, 5,684 in 2005-2009 and 9,764 in 2010-2014, before declining to 3,314 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 WETO-funded) wind energy patenting is in line with the broader trend in this technology, with little activity in the early periods in the analysis, followed by a rapid growth in the early part of this century. That said, the peak in DOE-funded patenting occurred earlier than that for overall patenting (2005-2009 versus 2010-2014).

Figure 4 - Total Number of Wind 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 Wind Energy Patent Families Funded by WETO/Other DOE by Priority Year

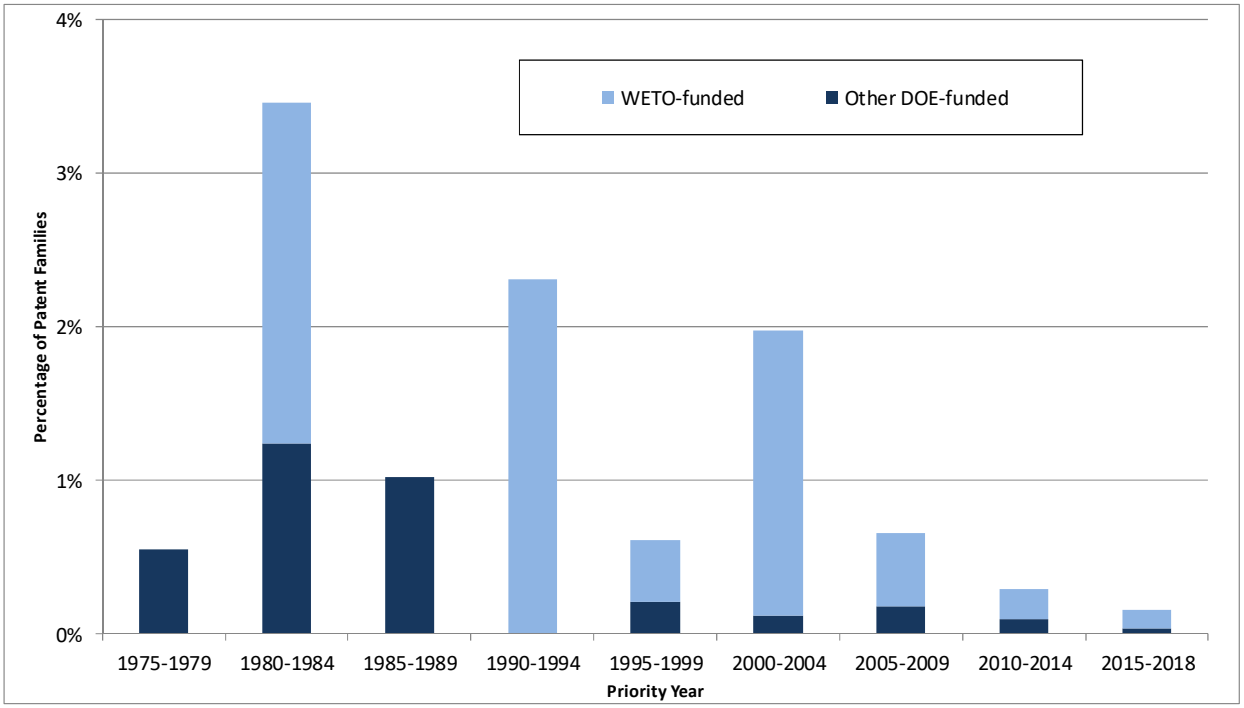


Figure 5 shows the percentage of wind energy patent families that were funded by DOE (WETO plus Other DOE). This percentage peaked at 3.5% in 1980-1984 (2.2% WETO-funded), although the numbers of patent families involved was small. Perhaps more interestingly, DOE-funded patent families were 2% of the total in 2000-2004 (1.9% WETO-funded), a period when wind energy patent activity started to increase. This suggests that WETO-funded research played an important part in the early stages of the growth in wind energy patenting. Since then, the percentage of wind energy patent families funded by DOE has declined, as overall patenting has increased while DOE-funded patenting has remained relatively steady. Overall, 0.6% of all wind energy patent families filed in 1976-2018 were funded by DOE.

Leading Wind Energy Assignees

The ten leading patenting companies in wind energy are listed above in Table 4, along with their number of wind energy patent families. Figure 6 shows the same information in graphical form, while also including DOE-funded patent families. The wind energy patents of these top ten companies form the basis for the backward tracing element of the analysis, as outlined below.

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

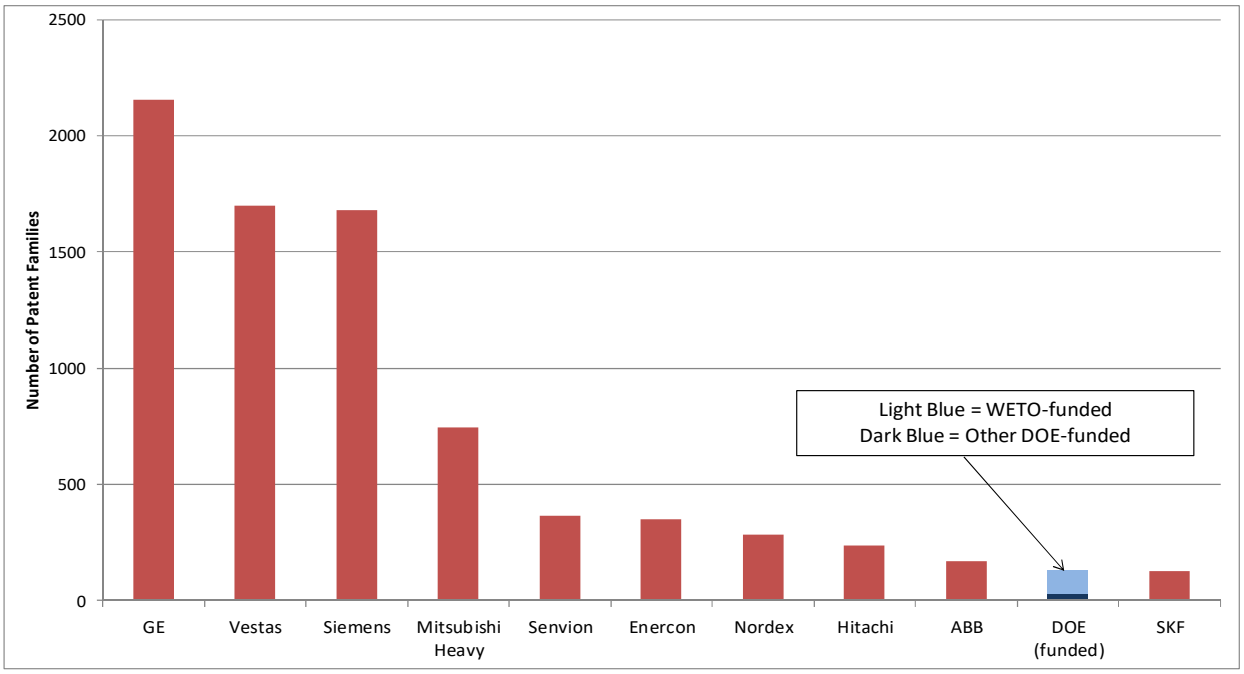


Figure 6 is dominated by three companies with the largest wind energy patent portfolios – General Electric (2,157 patent families), Vestas (1,699 families) and Siemens (1,680 families). They are followed by Mitsubishi Heavy Industries (744 wind energy patent families), with none of the other companies having more than 400 families. It is interesting to note the geographical distribution of the leading wind energy companies in Figure 6. Out of these ten companies, seven are based in Europe, two in Asia and only one in North America (although this company, General Electric, has the largest wind energy patent portfolio).

Figure 6 also shows that the DOE-funded wind energy portfolio of 130 patent families (98 WETO-funded; 32 Other DOE-funded) is smaller than those associated with nine out of the ten

leading companies, the exception being SKF. In assessing the impact of WETO-funded and Other DOE-funded wind energy patents, versus the impact of the patent portfolios associated with the leading companies, we therefore take into account this difference in portfolio size.

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 WETO (or another office within DOE). For example, General Electric and Siemens both have wind energy patent families that were partially or fully funded by WETO. In Figure 6, these patent families are counted in both the WETO segment of the DOE column, and in the respective company columns. This double-counting is appropriate, since these patent families are both funded by WETO and assigned to a leading company.

Assignees of WETO/Other DOE-funded Wind Energy Patents

The DOE-funded wind energy patent portfolios are constructed somewhat differently from the portfolios of the top ten companies listed in Figure 6. Specifically, DOE's 130 patent families are those funded by DOE, but they are not necessarily assigned to the agency. For example, WETO (or another DOE office) may have 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 and Siemens patent families discussed above).

Figure 7 shows the leading assignees on WETO-funded patent families. This chart is headed by General Electric with 31 patent families, followed by Northern Power Systems (10 families), Siemens (8 families) and Clipper Windpower (6 families). Figure 7 also features two organizations with WETO-funded wind energy patent families resulting from their management of DOE's National Renewable Energy Laboratory (NREL) – the Alliance for Sustainable Energy and MRIGlobal (formerly Midwest Research Institute). Figure 7 thus reflects the range of organizations that have carried out WETO-funded wind energy research.

Figure 7 - Assignees with Largest Number of WETO-Funded Wind Energy Patent Families

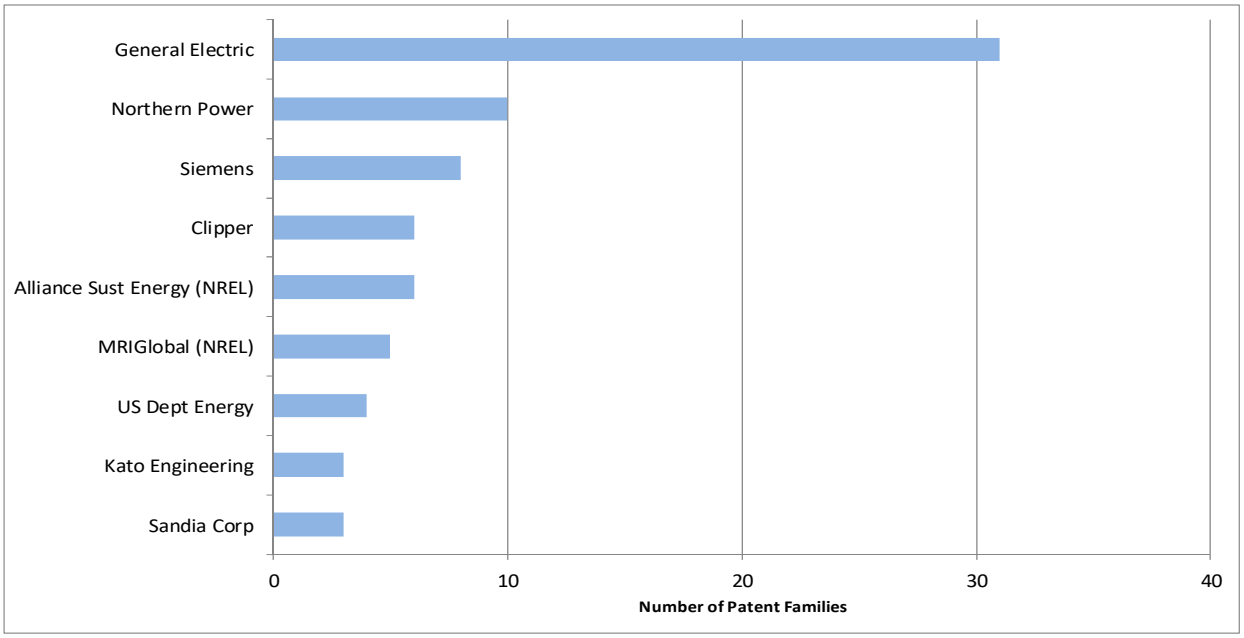
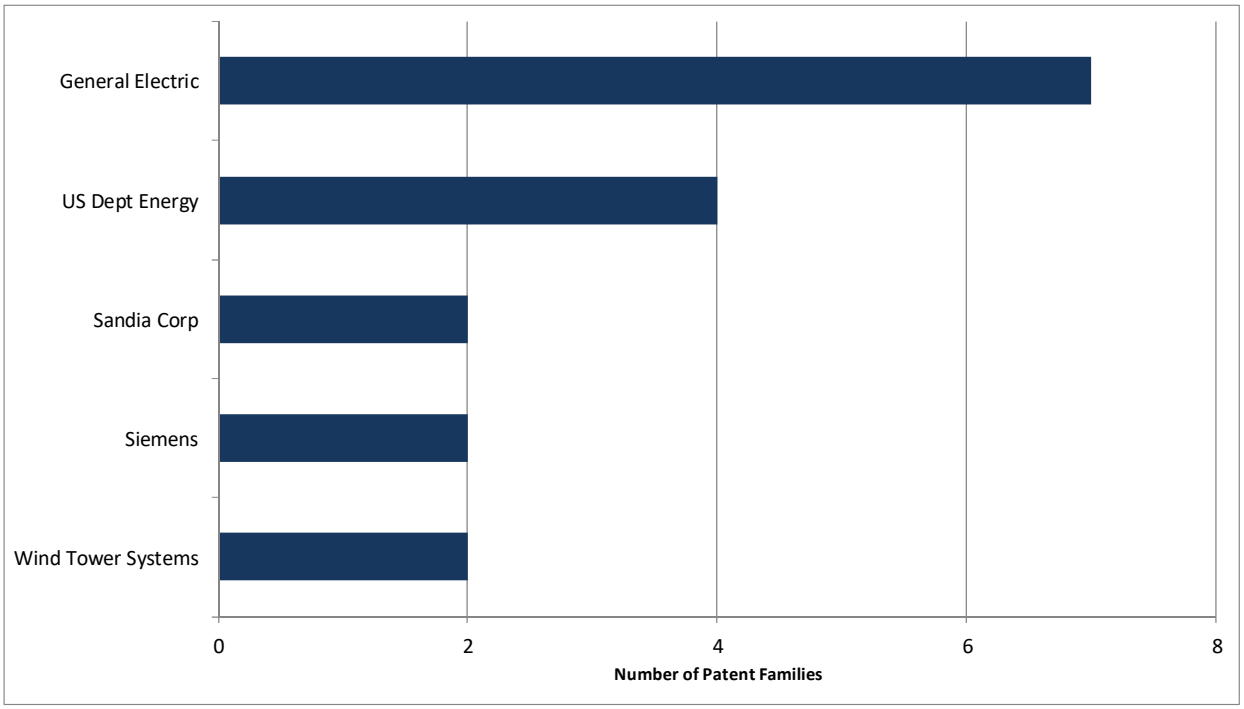


Figure 8 shows the leading assignees on Other DOE-funded wind energy patent families. The numbers of patent families in this figure are lower than for the WETO-funded assignees in Figure 7, since there are fewer Other DOE-funded families overall. Figure 8 is again headed by General Electric, with seven Other DOE-funded patent families. Siemens is also again present, with two patent families. DOE itself is in second place in Figure 8, with four 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.

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



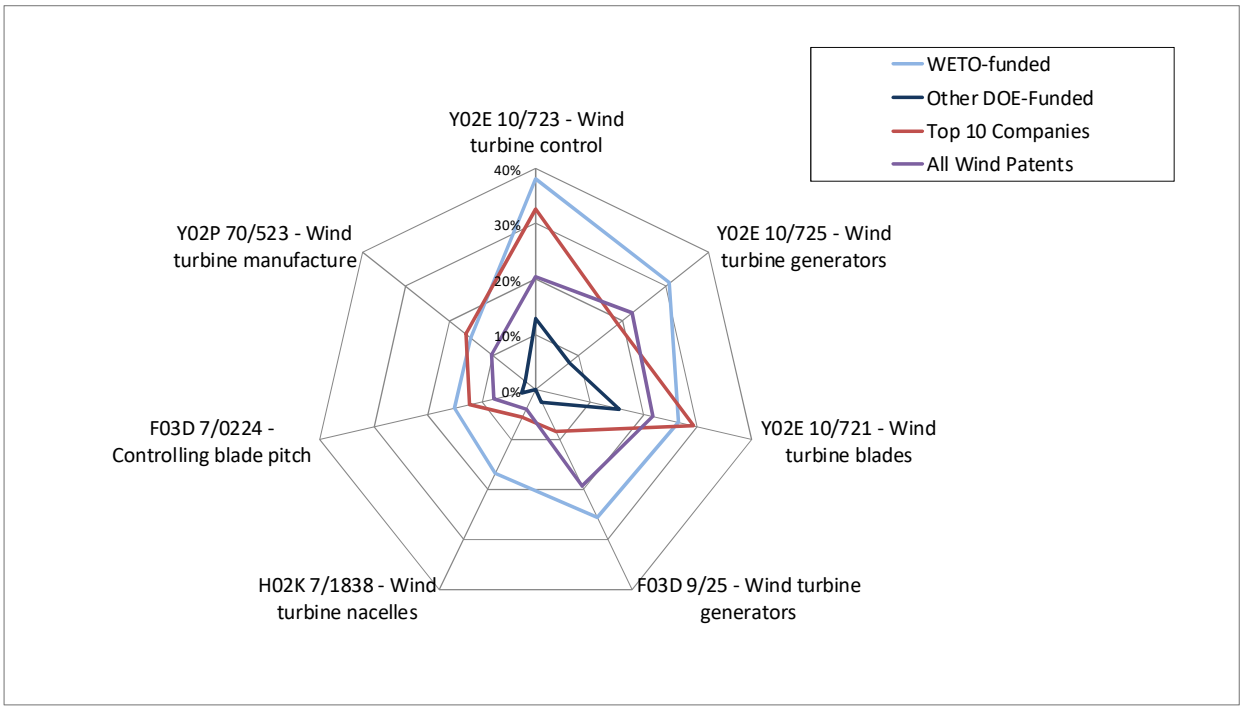
Distribution of Wind Energy Patents across Patent Classifications

We analyzed the distribution of WETO-funded wind energy U.S. patents across Cooperative Patent Classifications (CPCs).[7] We then compared this distribution to those associated with Other DOE-funded wind energy patents; wind energy patents assigned to the ten leading companies; and the universe of all wind energy patents. This analysis provides insights into the technological focus of WETO funding in wind energy, versus the focus of the rest of DOE, leading wind energy companies, and wind energy 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 WETO-funded wind energy patents. The purpose of this chart is thus to show the main focus areas of WETO-funded wind energy research, and the extent to which these areas translate to other portfolios (Other DOE-funded; leading wind energy companies; all wind energy).

[7] 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.

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



This figure shows that WETO-funded research includes relatively balanced coverage across the seven CPCs (which is not particularly surprising, since the WETO-funded patent portfolio forms the basis for the CPCs included in the chart). The most common CPC among WETO-funded wind energy patents is Y02E 10/723, which appears on 38% of these patents. This CPC is related to wind turbine control systems. Other CPCs in Figure 9 are related to different wind turbine components, including generators (Y02E 10/725 and F03D 9/25), blades (Y02E 10/721 and F03D 7/0224) and nacelles (H02K 7/1838). The leading companies, and wind energy patents overall, have a notable presence across these CPCs, with the exception of nacelles, where they have a lower percentage of patents. This suggests that, in the period 1976-2018, WETO funding helped to address a research gap related to nacelle technology. Meanwhile, Other DOE-funded patents are focused primarily on wind turbine blades and control systems.

Figure 10 is similar to Figure 9, except that it is from the perspective of the most common CPCs among all wind energy patents. Hence, the purpose of this chart is to show the main research areas within wind energy as a whole, and how these areas are represented in selected wind energy portfolios (WETO-funded; Other DOE-funded; leading wind energy companies). The four most common CPCs among all wind energy patents also appeared in Figure 9, and are concerned with wind turbine blades, generators and control systems. Hence, these are areas of overlap between the WETO-funded patent portfolio and wind energy patents in general. Figure 10 also includes CPCs related to onshore wind turbines (Y02E 10/728), wind turbine towers (F03D 13/20) and perpendicular rotation (i.e. vertical axis) wind turbines (Y02E 10/74). There are a number of WETO-funded patents in the first two of these CPCs, but fewer related to perpendicular rotation wind turbines.

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

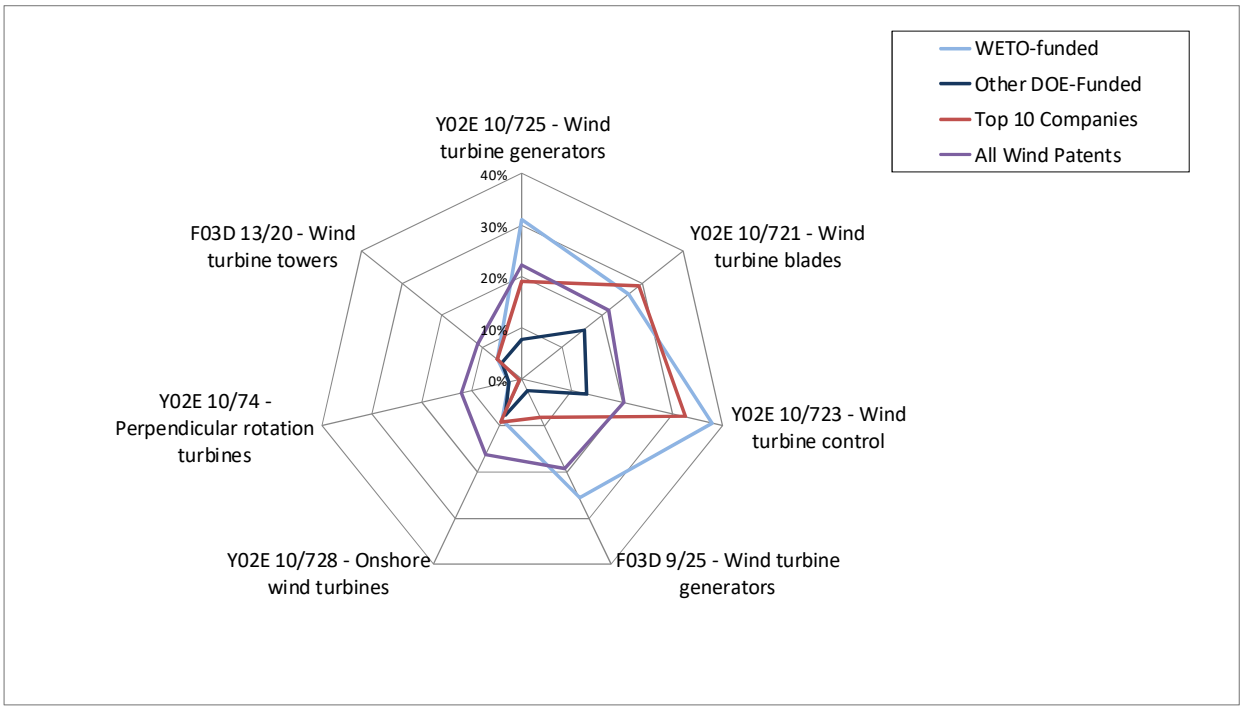


Figure 11 - Percentage of WETO-funded Wind Energy U.S. Patents in Most Common Cooperative Patent Classifications across Two Time Periods

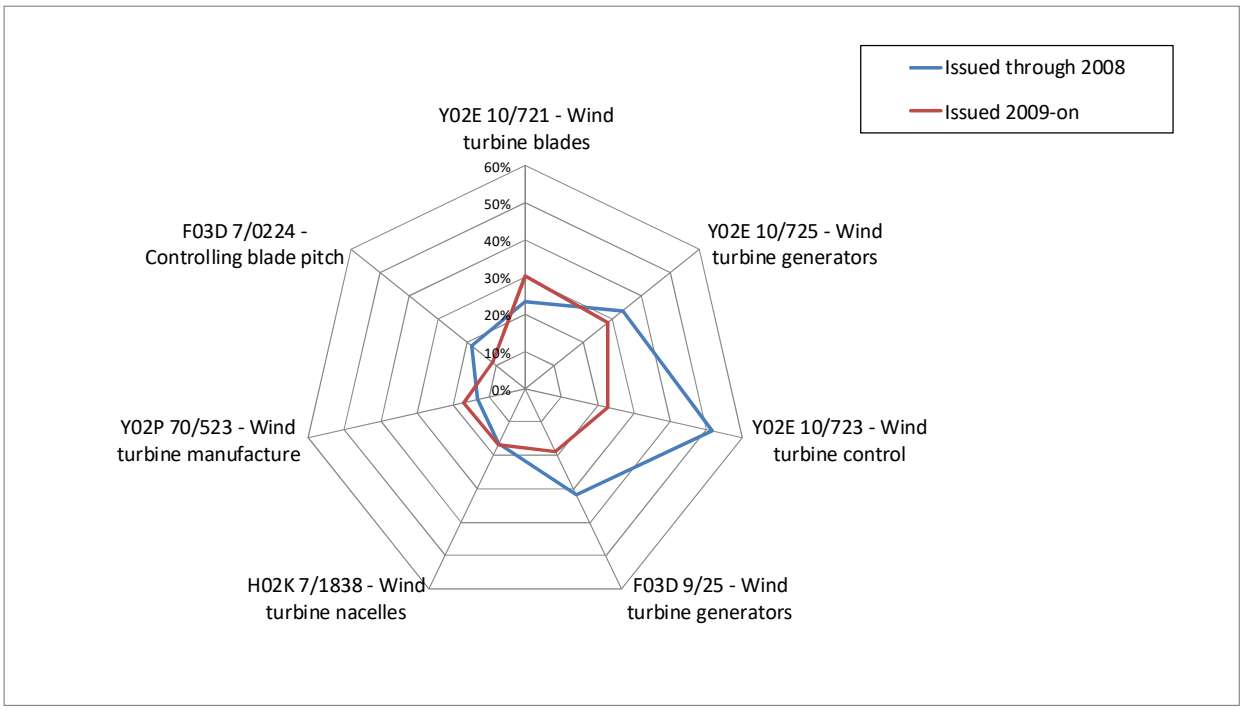


Figure 11 compares the CPC distribution of WETO-funded wind energy U.S. patents across two time periods – patents issued through 2008, and those issued from 2009 onwards (these dates are

selected to divide the patents into two groups of approximately equal size). This figure reveals that the CPCs associated with WETO-funded patents have been relatively consistent over time, with similar percentages of patents in each CPC across the two time periods. That said, there are some differences, notably a greater percentage of patents in the earlier time period related to wind turbine control (CPC Y02E 10/723) and generators (CPC F03D 9/25).

Tracing Backwards from Wind Energy Patents Owned by Leading Companies

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

Organizational Level Results

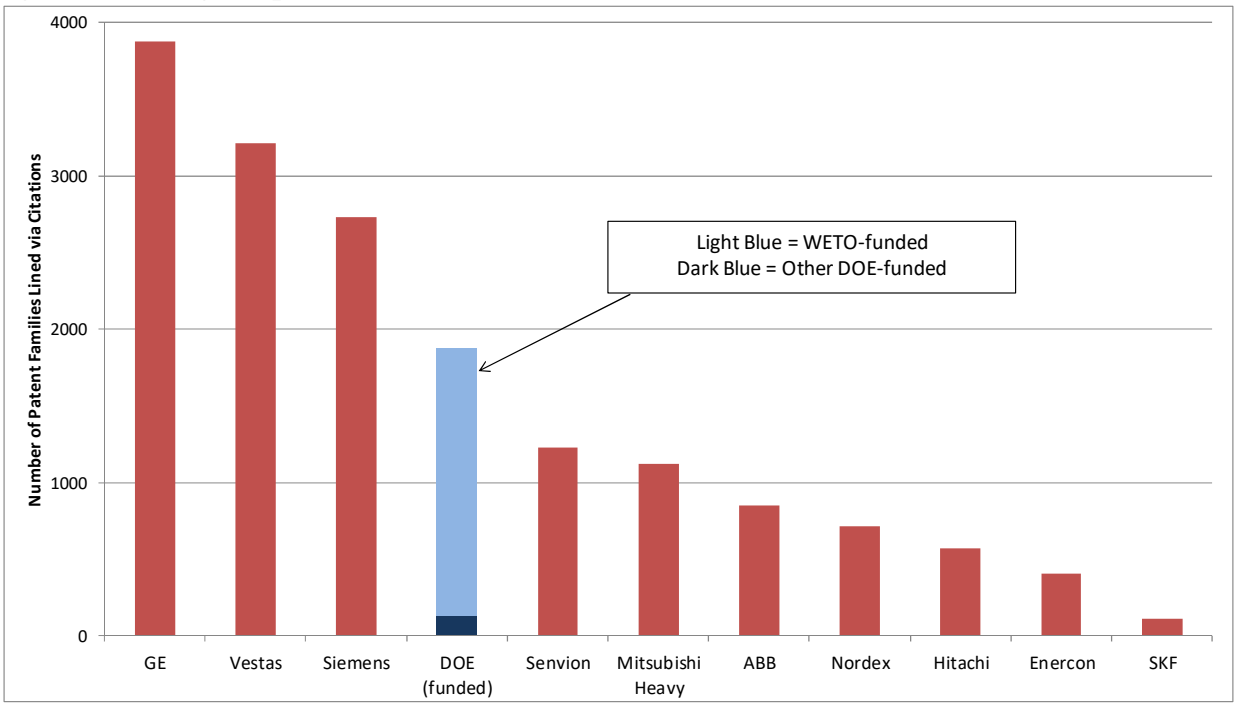
In the organizational level results, we first compare the influence of WETO-funded and Other DOE-funded wind energy research against the influence of leading wind energy companies. We then look at which of these leading companies build particularly extensively on DOE-funded wind energy research.

Figure 12 compares the influence of DOE-funded wind energy research to the influence of research carried out by the top ten wind energy companies. Specifically, this figure shows the number of wind energy patent families owned by the leading companies that are linked via citations to earlier wind 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 wind energy technology.[8]

In total, 1,874 leading company wind energy patent families (i.e. 8.4% of these 22,191 families) are linked via citations to earlier DOE-funded wind energy patents, out of which 1,740 are linked to WETO-funded wind energy patents. This finding puts DOE-funded patents in fourth place in Figure 12. The figure is headed by General Electric, with 3,877 leading company patent families linked to its earlier patents, followed by Vestas (3,212 linked families) and Siemens (2,727 linked families).

[8] This figure compares the influence of patents *funded* by WETO/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 and Siemens were funded by DOE. Also, in Figures 12 and 14-16, leading company patent families linked to both WETO-funded and Other DOE-funded patents are allocated to the WETO-funded segment of the DOE column, in order to avoid double-counting these families.

Figure 12 - Number of Leading Company Wind Energy Patent Families Linked via Citations to Earlier Wind Energy Patents from each Leading Company
e.g. 1,874 leading company families are linked to earlier WETO/Other DOE-funded families



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 many more patent families are linked via citations to General Electric than to DOE, since General Electric has sixteen times as many wind energy patent families available to be cited as prior art. 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 wind energy patent families (the majority of which are WETO-funded) are each linked to over fourteen patent families assigned to the leading companies. This puts DOE at the head of Figure 13 by a wide margin, with an average almost three times as high as ABB in second place. It means that, on average, more wind energy patent families owned by leading companies are linked via citations to each DOE-funded wind energy patent family than are linked to the wind energy patent families assigned to any other leading company Figure 13 thus suggests that, taking into account its relatively small size, the portfolio of DOE-funded wind energy patents has helped form an important part of the foundation for wind energy research carried out by the leading companies.

Figures 14 through 16 examine which of the leading companies build particularly extensively on earlier DOE-funded patents. Figure 14 shows how many wind energy patent families owned by each of the leading companies are linked via citations to at least one earlier DOE-funded wind energy patent. Out of the ten leading wind energy companies, General Electric, Vestas and Siemens are linked particularly strongly to earlier DOE-funded patents, suggesting that they build most extensively on earlier DOE-funded wind energy research. In total, 794 of General Electric's wind energy patent families are linked via citations to earlier DOE-funded wind

energy patents, 740 of which are linked to WETO-funded patents. Vestas has 380 patent families linked to DOE (345 to WETO), while Siemens has 316 families linked to DOE (296 to WETO).

Figure 13 - Average Number of Leading Company Wind Energy Patent Families Linked via Citations to Wind Energy Families from Each Leading Company
e.g. on average, each DOE-funded family is linked to 14 subsequent leading company families

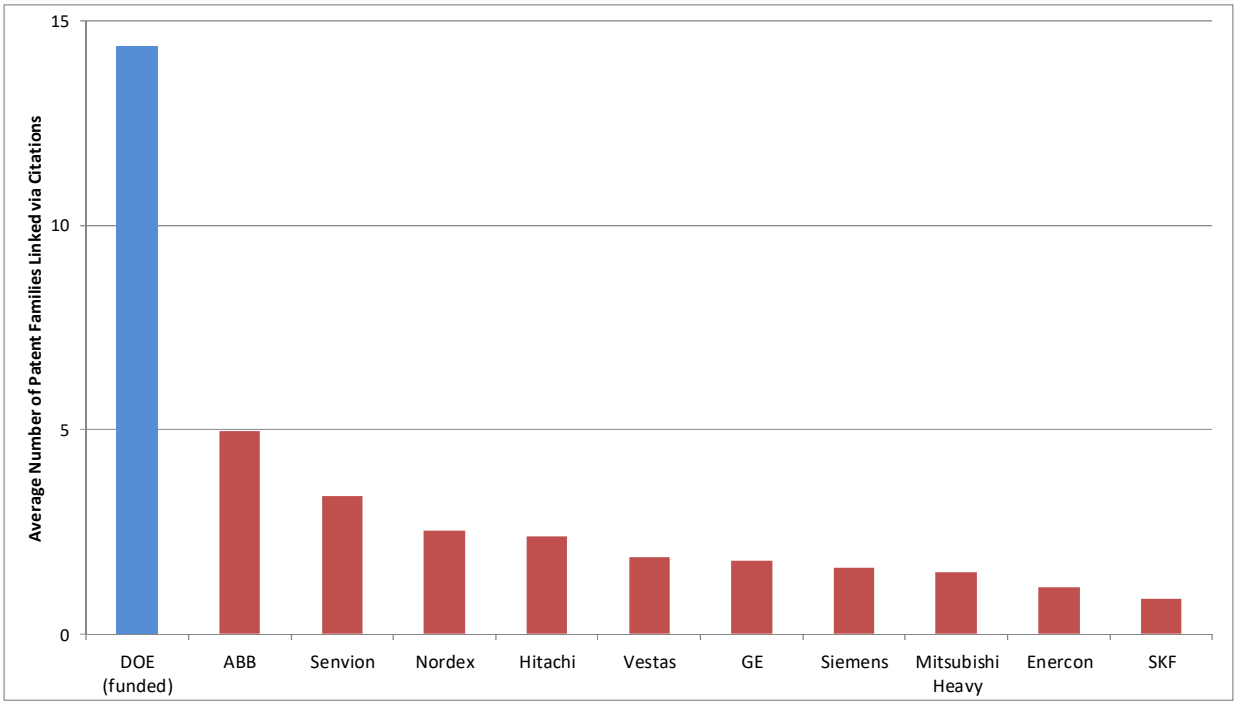


Figure 14 - Number of Patent Families Linked via Citations to Earlier WETO/Other DOE-funded Wind Energy Patents for each Leading Wind Energy Company

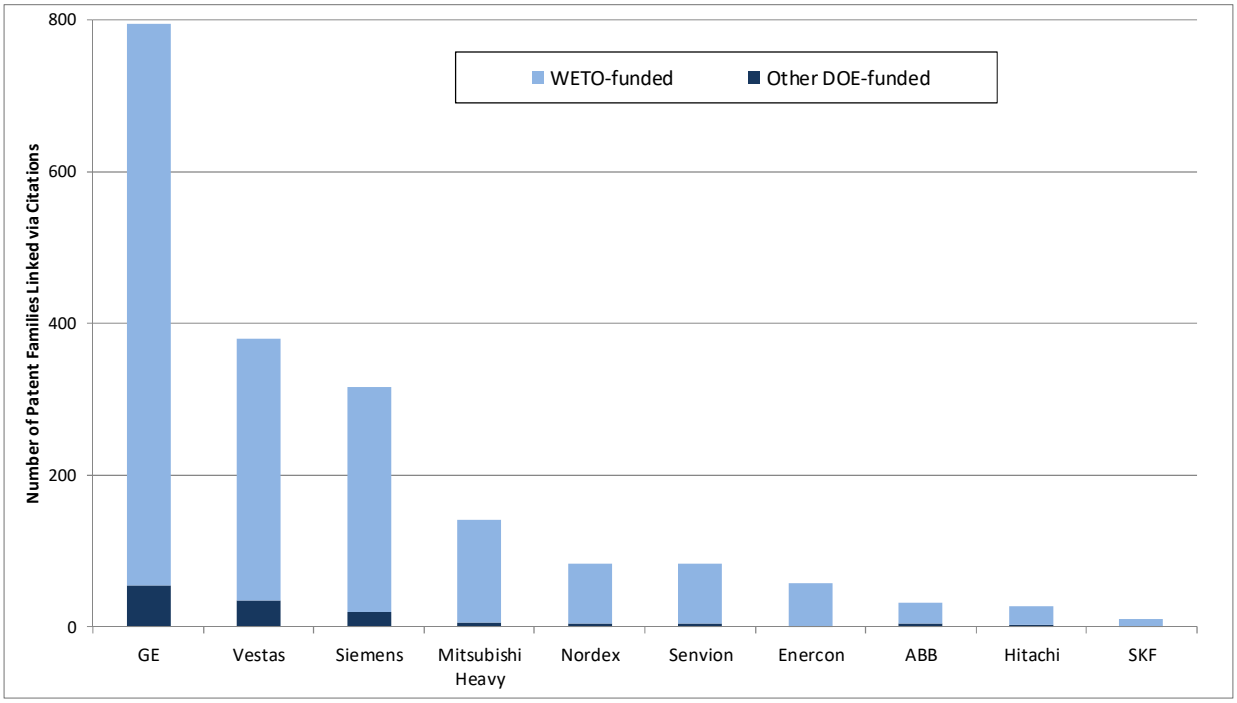
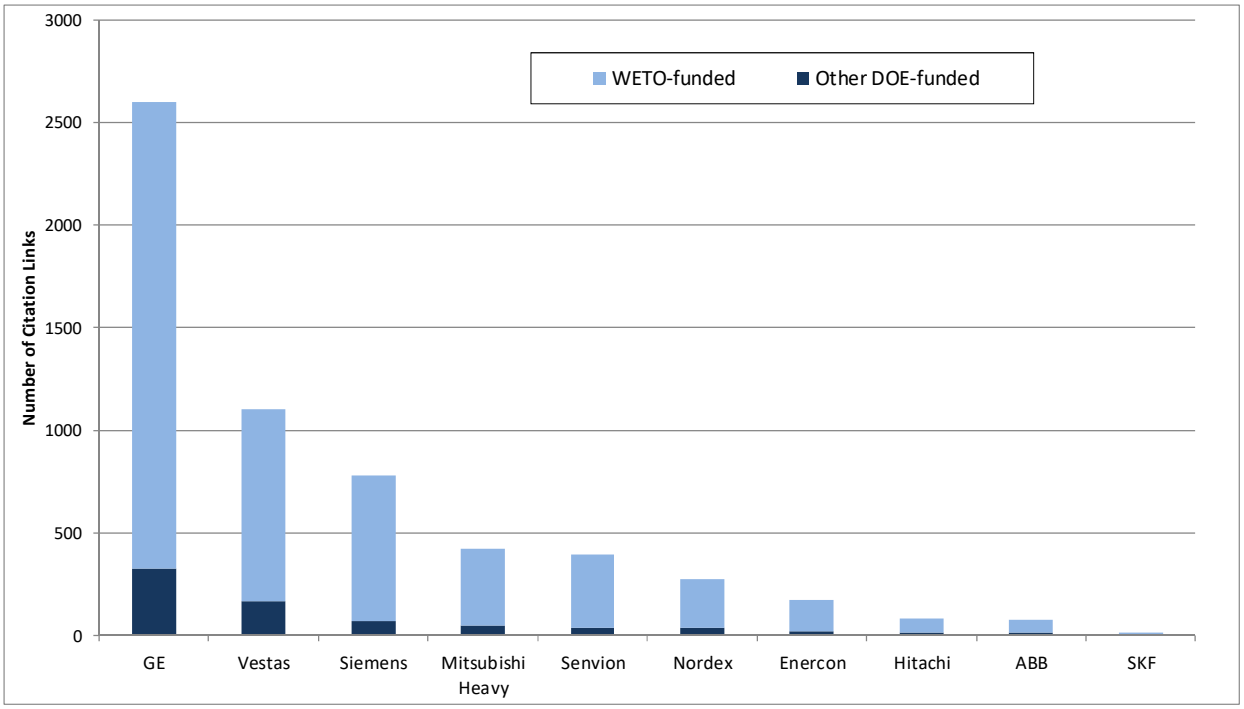


Figure 15 counts the total number of citation links from leading companies to earlier DOE-funded patents. This differs slightly from the count of linked families in Figure 14, since a single patent family may be linked to multiple earlier DOE-funded patents. The same three companies are at the head of Figure 15 – General Electric, Vestas and Siemens – reinforcing their close links to earlier DOE-funded wind energy research. General Electric leads by a wider margin in this figure, with 2,598 citation links to DOE-funded wind energy patents, 2,271 of which are links to WETO-funded patents.

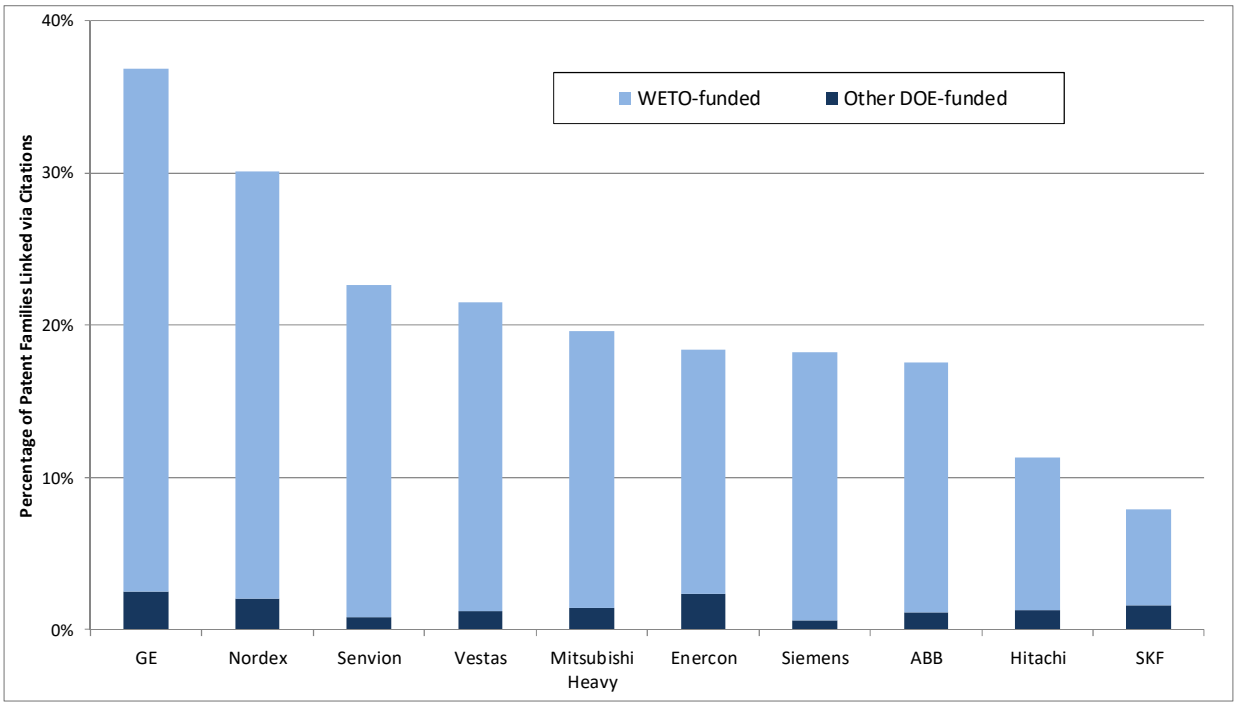
Figure 15 - Number of Citation Links from Leading Wind Energy Company Patent Families to Earlier WETO/Other DOE-funded Wind Energy Patents



There is an element of portfolio size bias in the patent family counts in Figures 14 and 15. Companies with larger wind 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 wind energy patent families that are linked via citations to earlier DOE-funded wind 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 strong links from General Electric's wind energy patent families to earlier DOE-funded research. In total, 36.8% of General Electric's wind energy patent families are linked via citations to DOE-funded wind energy patents (34.3% linked to WETO-funded patents). Nordex and Senvion are also prominent in Figure 16. The former has 30.1% of its patent families linked to earlier DOE-funded patents (28.0% to WETO) while the latter has 22.6% of its patent families linked to DOE (21.8% to WETO), Meanwhile, Siemens is somewhat less prominent in Figure 16, with its higher position in Figure 14 and Figure 15 resulting in part from the size of its patent portfolio.

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

Table 5 shows the WETO-funded wind 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 WETO-funded technologies that are linked to many subsequent innovations associated with leading companies in the wind energy industry. The WETO-funded patent family linked to the most leading company families is assigned to MRIGlobal (formerly Midwest Research Institute), through its management of NREL. This patent family (whose representative patent[9] is US #5,798,632) was filed in 1995 and describes a variable speed wind turbine. It is linked via citations to 371 subsequent patent families assigned to the leading companies, including families from nine out of these ten companies (i.e. all except SKF). The second patent family in Table 5 (representative patent US #4,435,646) describes an automatic pitch control system for wind turbines. It was filed in 1982 and assigned to Northern Power Systems. This patent family is linked via citations to 317 families assigned to the leading companies, including families from each of these companies. Clipper Windpower (now owned

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

by Platinum Equity) is the assignee on the next two patent families in Table 5, describing a variable speed wind turbine (representative patent US #7,042,110) and turbine operation during electrical faults (representative patent US #7,233,129). These families are linked via citations to 265 and 223 leading company families respectively. General Electric also has a number of patent families in Table 5, describing a variety of technologies including turbine control (representative patent US #7,342,323), vibration damping (representative patent US #7,309,930) and ice detection (representative patent US #7,086,834).

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

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
24003638	5798632	1995	371	MRIGlobal (NREL)	Variable speed wind turbine generator with zero-sequence filter
23382881	4435646	1982	317	Northern Power	Wind turbine rotor control system
34679397	7042110	2003	265	Clipper Windpower	Variable speed distributed drive train wind turbine system
34681755	7233129	2003	223	Clipper Windpower	Generator with utility fault ride-through capability
36928409	7342323	2005	186	General Electric	System and method for upwind speed based control of a wind turbine
23152877	4410806	1981	184	US Dept Energy	Control system for a vertical axis windmill
29715422	7071579	2002	170	Global Energy Concepts	Wind farm electrical system
32771011	7160083	2003	170	General Electric	Method and apparatus for wind turbine rotor load control
34981372	7309930	2004	170	General Electric	Vibration damping system and method for variable speed wind turbines
35455150	7086834	2004	157	General Electric	Methods and apparatus for rotor blade ice detection
25312016	5354175	1992	155	Northern Power	Wind turbine rotor hub and teeter joint

Table 5 lists WETO-funded patents linked to large numbers of subsequent wind energy patent families owned by leading companies. Table 6 looks in the opposite direction, and lists wind energy patent families owned by leading companies that are linked particularly extensively to earlier patents funded by WETO. This table is headed by a 2014 Senvion patent family (representative patent US #9,394,882) describing structural preforms used to manufacture wind turbine components. It is linked via citations to 40 earlier WETO-funded patent families, notably General Electric and Northern Power Systems families for wind turbine rotors. The second patent family in Table 6 is assigned to General Electric and describes a method for attaching components to a wind turbine blade. It is linked to 27 earlier WETO-funded patent families, including earlier General Electric families for wind turbine control and 3-Tex families for wind turbine component manufacturing.

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

Patent Family #	Representative Patent #	Priority Year	# WETO Fams	Assignee	Title
43759938	9394882	2014	40	Senvion	Wind turbine rotor blade components and methods of making same
55913537	9869296	2015	27	General Electric	Attachment method and system to install components to a wind turbine blade
50239455	9889619	2014	25	Siemens	Method for manufacturing a rotor blade for a wind turbine
46126776	8491262	2011	19	General Electric	Method for shut down of a wind turbine having rotor blades with fail-safe air brakes
54930016	9745958	2014	18	General Electric	Method and system for managing loads on a wind turbine
46027738	9279413	2012	16	Siemens	Wind turbine
34908870	7692322	2004	16	Mitsubishi Heavy Ind	Wind turbine generator, active damping method thereof, and windmill tower
46652126	9222464	2011	15	Mitsubishi Heavy Ind	Controller for wind turbine generator
39027518	7851934	2006	14	Vestas Wind	Method for controlling a wind turbine connected to the utility grid, wind turbine and wind park
35721676	7268443	2004	13	Hitachi	Wind turbine generator system

We also identified high-impact wind energy patents owned by leading companies that have citation links back to WETO-funded patents.[10] The idea is to highlight important technologies owned by leading companies that are linked to earlier wind energy research funded by WETO. Table 7 lists wind energy patents owned by leading companies that have Citation Index values of three or over (i.e. they have been cited at least three times as frequently as expected), and are linked via citations to earlier WETO-funded wind energy patents. The patents are listed in descending order based on their Citation Index.

The patent at the head of Table 7 (US #6,670,721) is assigned to ABB and describes a conversion system for generating electrical power from renewable sources such as wind turbines. Since this ABB patent was issued in 2003, it has been cited as prior art by 163 subsequent patents, which is more than seven times as many citations as expected given its age and technology. In turn, this patent is linked via citations to an earlier MRIGlobal (NREL) patent family outlining variable speed wind turbines. The second patent in Table 7 (US #6,566,764) is

[10] 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 F03D 9/25 (Wind turbine generators) 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.

assigned to Vestas and describes a variable speed turbine. This patent is linked via citations to earlier WETO-funded patent families for vertical axis wind turbines assigned to DOE and variable speed turbines assigned to MRIGlobal (NREL). In turn, it has been cited as prior art by 144 subsequent patents, more than six times as many citations as expected. General Electric has a series of highly-cited patents in Table 7. These range in age from a 1999 patent for wind turbine braking (US #5,907,192) to a 2013 patent (US 8,414,261) for noise reduction, both of which are linked to earlier Northern Power patent families for wind turbine rotor control.

Table 7 - Highly Cited Leading Company Wind Energy Patents Linked via Citations to Earlier WETO-funded Wind Energy Patents

Patent	Issue Year	# Cites Received	Citation Index	Assignee	Title
6670721	2003	163	7.66	ABB Ltd	System, method, rotating machine and computer program product for enhancing electric power produced by renewable facilities
6566764	2003	144	6.77	Vestas Wind	Variable speed wind turbine having a matrix converter
7423412	2008	60	5.15	General Electric	Method, apparatus and computer program product for injecting current
8414261	2013	20	5.01	General Electric	Noise reducer for rotor blade in wind turbine
5907192	1999	109	4.01	General Electric	Method and system for wind turbine braking
7217091	2007	49	3.94	General Electric	Methods and apparatus for deicing airfoils or rotor blades
7298059	2007	44	3.86	General Electric	System and method for operating a wind farm under high wind speed conditions
7387491	2008	46	3.43	General Electric	Active flow modifications on wind turbine blades
7198471	2007	43	3.38	Vestas Wind	Wind turbine blade
7692322	2010	31	3.06	Mitsubishi Heavy Industries	Wind turbine generator, active damping method thereof, and windmill tower

While the patent-level results focus on WETO-funded wind energy patent families, we also identified Other DOE-funded wind 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 the six patent families at the head of this table are all marked as "unknown" for WETO funding, rather than being definitively not WETO-funded. As such, while these families are defined as Other DOE-funded, some may in fact have been funded by WETO.

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

Patent Family #	Representative Patent #	Priority Year	# Linked Families	Assignee	Title
24811296	4651017	1985	232	US Dept Energy	Wind energy conversion system
24873660	4083651	1976	120	United Technologies	Wind turbine with automatic pitch and yaw control
23459350	5570859	1995	119	Unassigned	Aerodynamic braking device
22996301	4366386	1981	93	Windfree Inc	Magnus air turbine system
25406389	4228391	1978	54	US Dept Energy	Induction machine
24765334	4677364	1985	38	US Dept Energy	Reactive power compensating system
39125245	7983799	2006	20	General Electric	System and method for controlling microgrid
38345609	7877934	2005	17	Wind Tower Systems	Lifting system and apparatus for constructing wind turbine towers

Table 8 is headed by a 1985 patent family (representative patent US #4,651,017) assigned to DOE, which describes wind speed measurement for controlling wind turbines. This patent family is linked via citations to 232 subsequent families assigned to the leading companies, including families from nine out of these ten companies (i.e. all except SKF). The second patent family in Table 8 (representative patent US #4,083,651) is one of the oldest in the analysis, having been filed in 1976. It is assigned to United Technologies and describes a system for controlling blade pitch and yaw in a wind turbine. This patent family is linked to 120 subsequent families assigned to eight of the ten leading companies (all except ABB and Hitachi). The third patent family in Table 8 (representative patent US #5,570,859) is unassigned, which means that the rights are owned by its inventor. This patent family describes a wind turbine braking device, and is linked to 119 families owned by seven of the leading companies (all except ABB, Senvion and SKF).

Overall, the backward tracing element of the analysis suggests that, taking into account their relatively small size, the portfolios of WETO-funded and Other DOE-funded wind energy patents have had an important influence on subsequent innovations associated with the leading wind energy companies. This influence can be seen both over time and across technologies, with a number of DOE-funded patent families linked via citations to patents assigned to many of the leading companies.

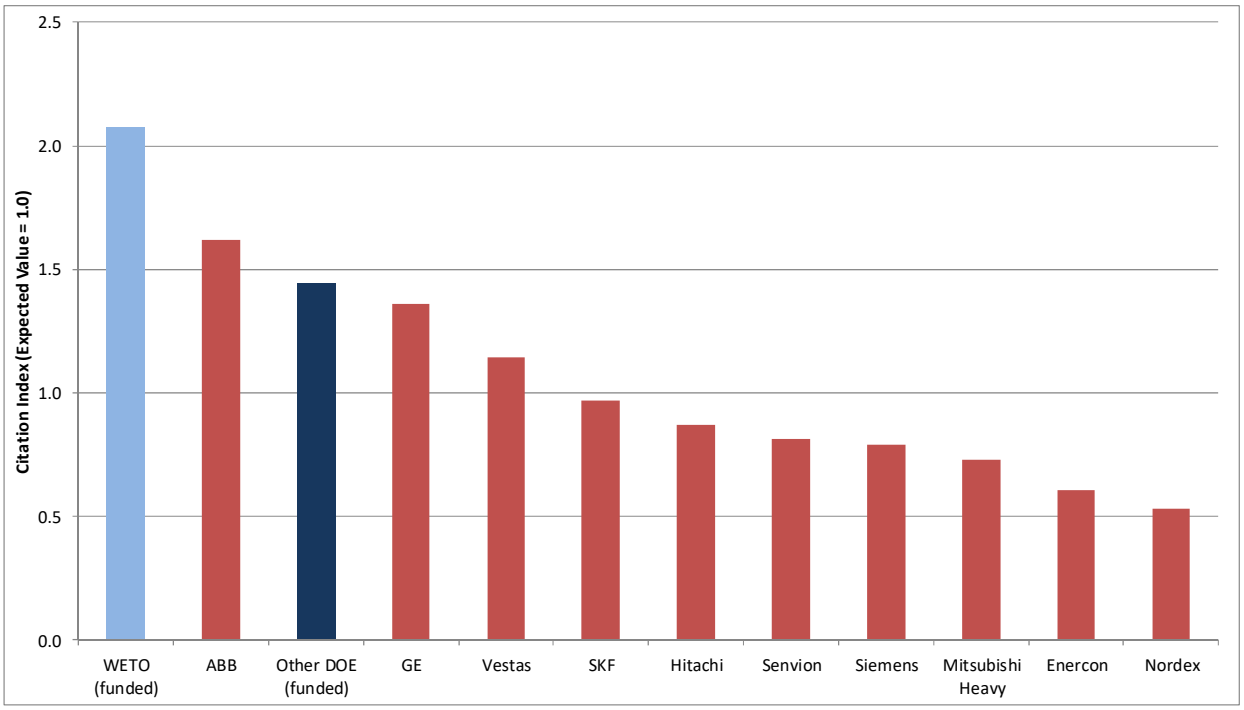
Tracing Forwards from DOE-funded Wind Energy Patents

The previous section of the report examined the influence of DOE-funded wind energy research upon technological developments associated with leading wind 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 WETO-funded (and Other DOE-funded) wind 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 wind energy companies), this section of the report examines on the broader influence of WETO-funded (and Other DOE-funded) wind energy research, both within and beyond the wind energy industry. Also, in order to avoid repeating earlier results, the forward tracing concentrates primarily on patents that are linked to DOE-funded wind energy research, but are not owned by the leading wind energy companies.

Organizational Level Results

We first generated average Citation Index values for the portfolios of WETO-funded and Other DOE-funded wind energy patents. We then compared these Citation Indexes against those of the ten leading wind energy companies. The results are shown in Figure 17. This figure reveals that both the WETO-funded and Other DOE-funded wind energy patent portfolios have high average Citation Index values compared to those of the ten leading companies. Indeed, the WETO-funded patents have a Citation Index of 2.07 (showing they have been cited more than twice as frequently as expected), which is higher than all of the leading companies. The Citation Index for Other DOE-funded wind energy patents is lower at 1.45, but this still means that these patents have been cited 45% more frequently than expected. This puts Other DOE-funded patents in third place in Figure 17, behind WETO and ABB (which has a Citation Index of 1.62).

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



The Citation Index measures the overall influence of the DOE-funded wind 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 wind energy patent families.[11] 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 WETO-funded wind energy patents. Typically, a figure such as this shows CPCs in two different colors – i.e. those related to wind energy technology and those beyond wind energy technology. The former represent the influence of WETO-funded patents on wind energy technology itself, while the latter represent spillovers of the influence of WETO-funded wind energy research into other technology areas.

In Figure 18, all of the CPCs are shown in a single color, since they are all connected in some way to wind energy. This suggests that wind energy is a relatively self-contained technology, with successive generations of technology building upon earlier research. That said, there are a number of different wind energy technologies represented in this figure, covering turbine control systems, generators, blades and transformers. This reflects the influence of WETO-funded patents across many different areas of wind energy technology.

[11] 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 wind energy patent families.

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

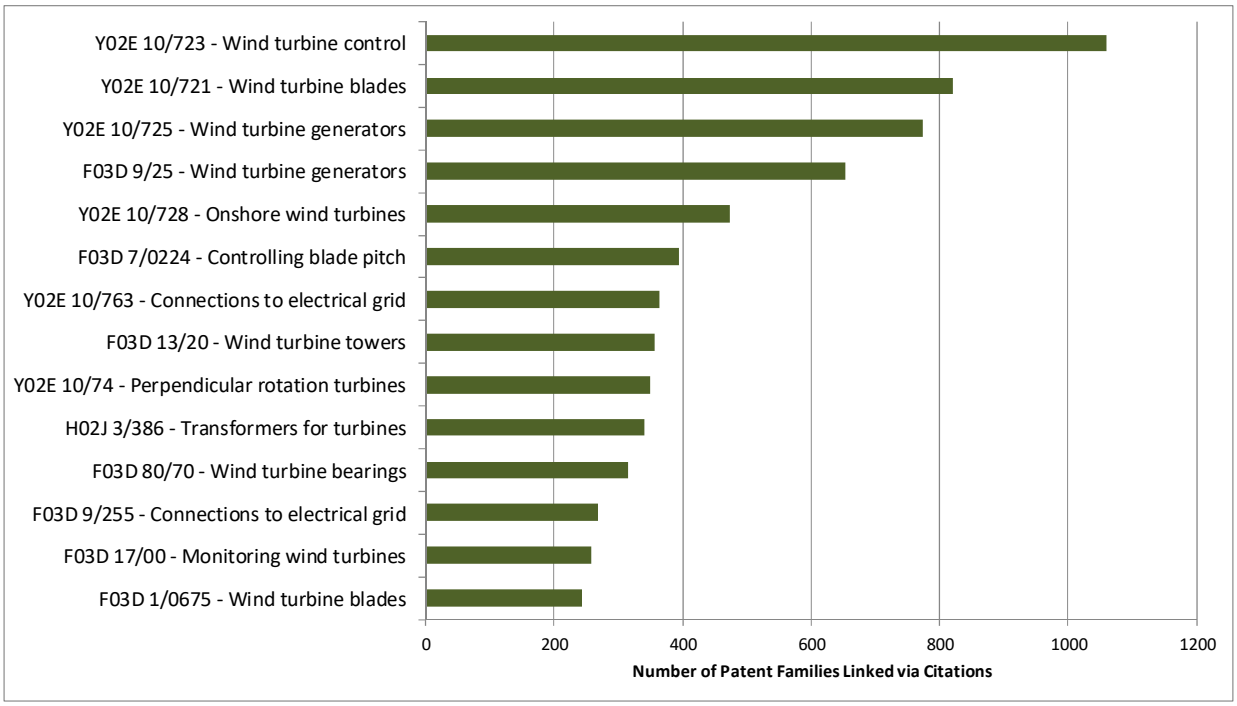


Figure 19 - Number of Patent Families Linked via Citations to Earlier Other DOE-Funded Wind Energy Patents by CPC

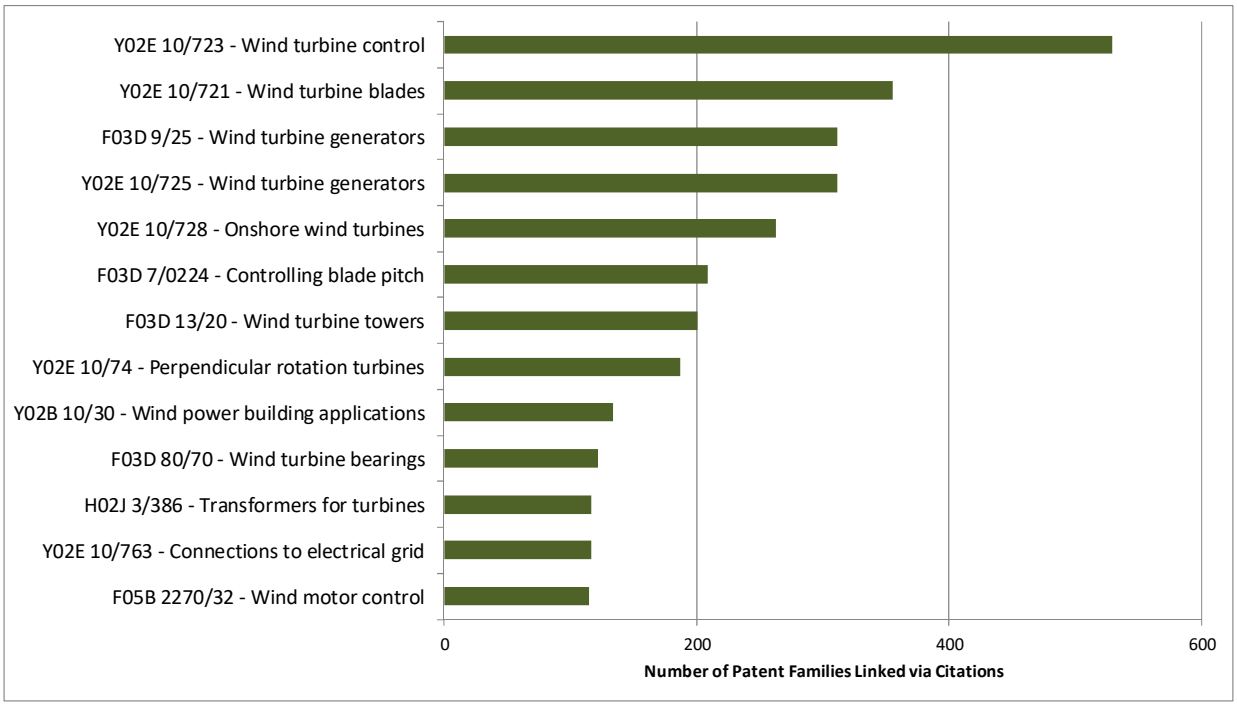
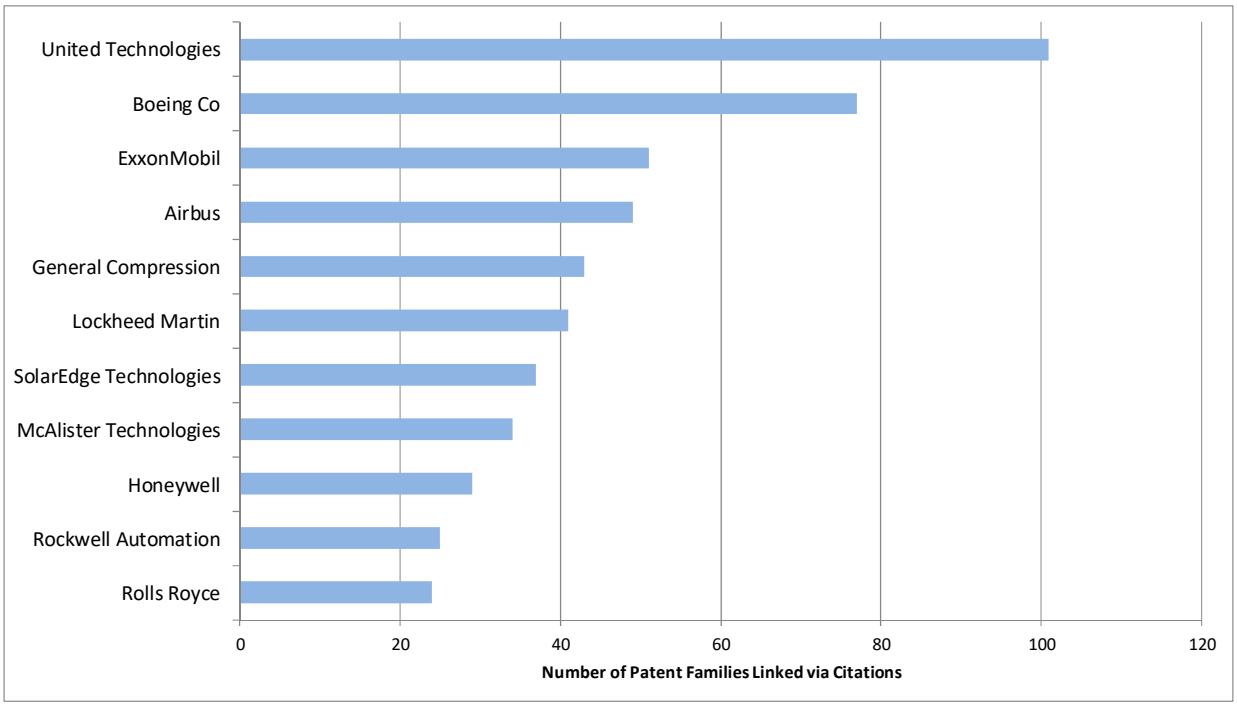


Figure 19 is similar to Figure 18, but is based on patent families linked to Other DOE-funded wind energy patents, rather than WETO-funded wind energy patents. All of the CPCs are again related to wind energy, and their distribution is similar to that of the families linked to WETO-

funded patents. Again, this shows the influence of Other DOE-funded patents on subsequent innovations across a range of wind energy technologies.

The organizations with the largest number of patent families linked via citations to earlier WETO-funded wind energy patents are shown in Figure 20. To avoid repeating the results from earlier, this figure excludes the ten leading wind 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 wind energy technology.

Figure 20 - Organizations with Largest Number of Patent Families Linked via Citations to WETO-funded Wind Energy Patents (excluding leading wind energy companies)

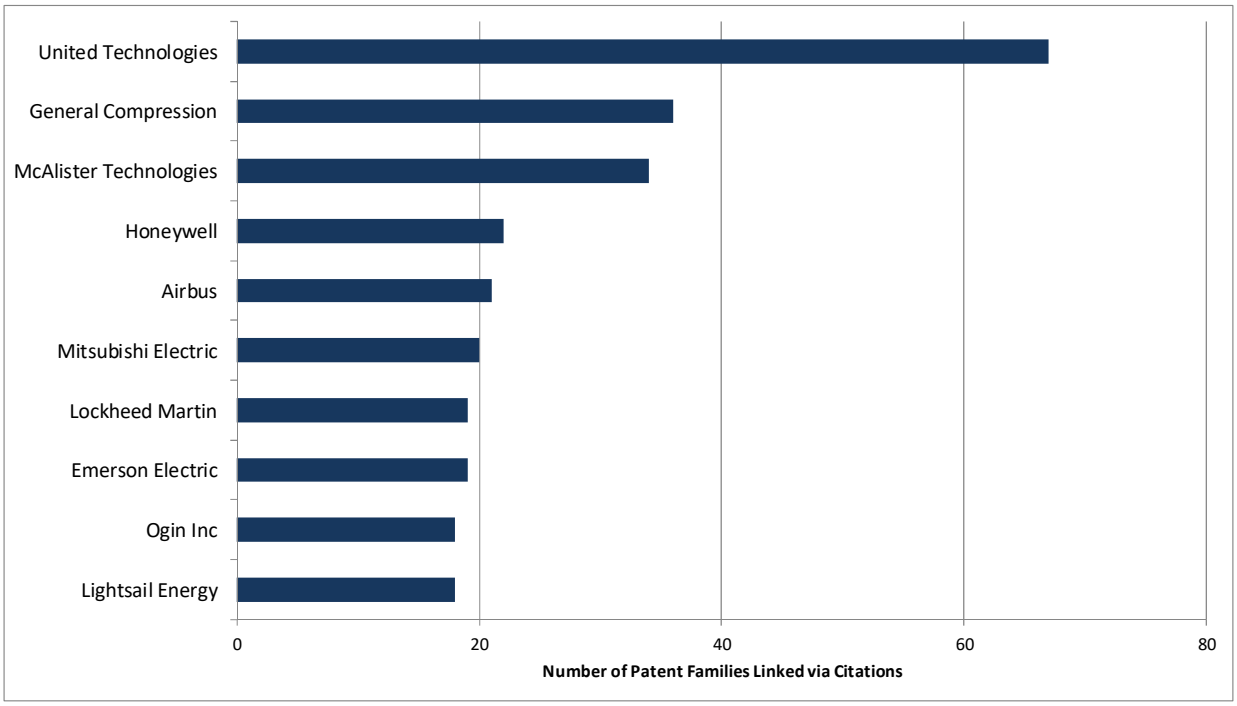


United Technologies is at the head of Figure 20, with 101 patent families linked via citations to earlier WETO-funded wind energy patents. These United Technologies patent families cover a range of technologies related to power generation, and are linked to earlier WETO-funded patents for wind turbine components assigned to various organizations, notably Clipper Windpower, General Electric and Northern Power Systems. Boeing is in second place in Figure 20, with 77 patent families linked via citations to earlier WETO-funded patents. Many of these Boeing families describe aerodynamic structures for use in aircraft, and are linked to earlier Northern Power Systems patents for improved wind turbine blades and ailerons. Similar citation links can also be seen between aircraft patent families assigned to Airbus (in fourth place in Figure 20) and the same WETO-funded Northern Power Systems patents. Meanwhile, ExxonMobil (in third place in Figure 20) has numerous patent families describing power generation that are linked to early WETO-funded patents assigned to DOE for wind-powered cooling towers. These are all examples of WETO-funded wind energy research influencing subsequent developments in technologies beyond wind energy.

Figure 21 shows the organizations with the largest number of patent families linked to earlier Other DOE-funded wind energy patents. This figure is again headed by United Technologies,

with 67 patent families linked via citations to earlier Other DOE-funded wind energy patents. These United Technologies families describe both power generation and wind energy technologies, and are linked via citations to earlier Other DOE-funded wind turbine component patents assigned to DOE. General Compression is in second place in Figure 21, with 36 patent families linked via citations to earlier Other DOE-funded wind turbine patents. Many of these General Compression patent families are related to energy storage, and are linked to early DOE patents for wind-powered pumps. McAlister Technologies has 34 patent families linked via citations to Other DOE-funded patents, putting it in third place in Figure 21. These McAlister families describe energy storage and production, and are linked to an early Iowa State University (Ames National Laboratory) patent for a tornado-type wind turbine.

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



Patent Level Results

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

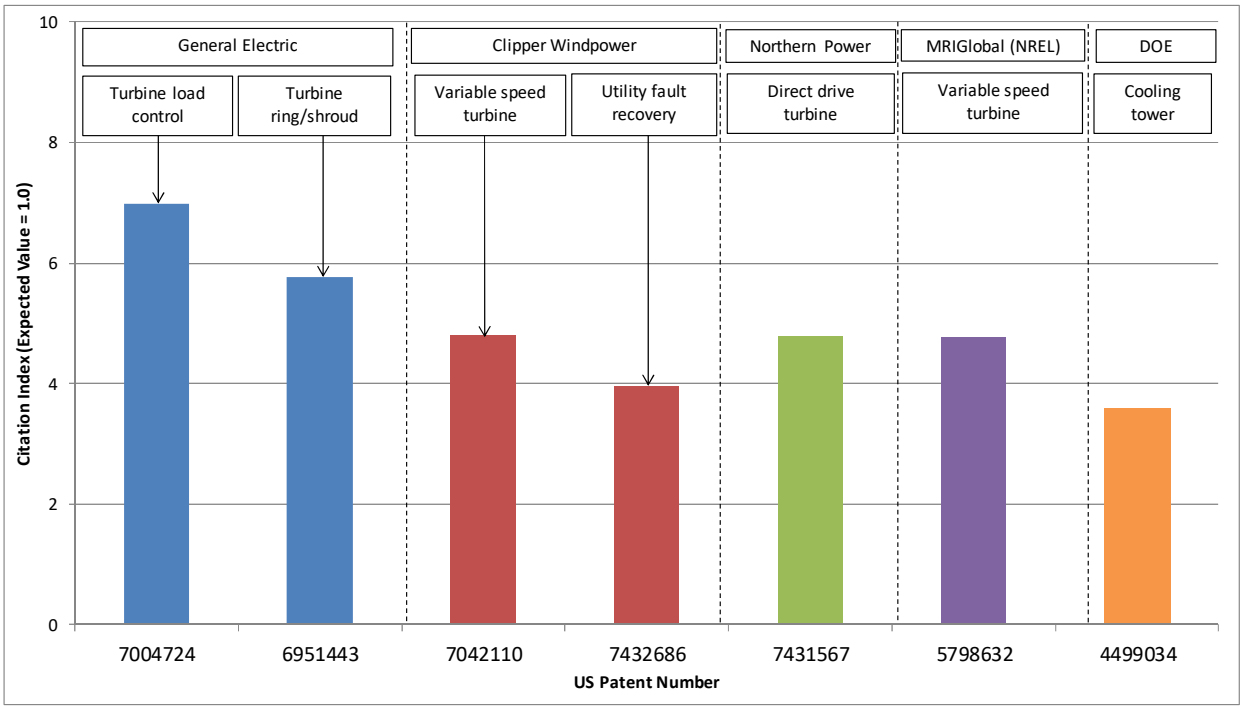
The simplest way of identifying high-impact WETO-funded wind energy patents is via overall Citation Indexes. The WETO-funded patents with the highest Citation Index values are shown in Table 9, with selected patents also presented in Figure 22. The patents in this table are a mix of older patents that 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.

Table 9 – List of Highly Cited WETO-Funded Wind Energy Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
7004724	2006	86	6.99	General Electric	Method and apparatus for wind turbine rotor load control based on shaft radial displacement
6951443	2005	77	5.77	General Electric	Wind turbine ring/shroud drive system
7086834	2006	61	4.85	General Electric	Methods and apparatus for rotor blade ice detection
7042110	2006	139	4.81	Clipper Windpower	Variable speed distributed drive train wind turbine system
7431567	2008	64	4.78	Northern Power Systems	Wind turbine having a direct-drive drivetrain
5798632	1998	134	4.76	MRIGlobal (NREL)	Variable speed wind turbine generator with zero-sequence filter
7432686	2008	46	3.95	Clipper Windpower	Wind turbine generator apparatus with utility fault ride-through capability
4499034	1985	54	3.58	US Dept Energy	Vortex-augmented cooling tower-windmill combination
5320491	1994	79	3.57	Northern Power Systems	Wind turbine rotor aileron

Figure 22 – Examples of Highly-Cited WETO-funded Wind Energy Patents



The patent at the head of Table 9 (US #7,004,724) is assigned to General Electric and describes a method for avoiding asynchronous loads in wind turbines. Since being issued in 2006, this patent has been cited as prior art by 86 subsequent patents, almost seven times as many citations as expected given its age and technology. This is one of three highly-cited WETO-funded General

Electric patents at the head of Table 9, with the others describing wind turbine rings and shrouds for load management (US #6,951,443) and a method for detecting ice on wind turbine rotors (US #7,086,834). Clipper Windpower has the patent in Table 9 with the highest raw number of citations (US #7,042,110), having been cited as prior art by 139 subsequent patents, almost five times as many as expected. This Clipper patent describes a variable speed wind turbine. MRIGlobal (NREL) also has a variable speed wind turbine patent in Table 9 (US #5,798,632), which has been cited by 134 subsequent patents (almost five times as many as expected).

The Citation Indexes in Table 9 are based on a single generation of citations to WETO-funded wind energy patents. Table 10 and Table 11 extend this by examining a second generation of citations – i.e. they show the WETO-funded wind energy patents linked directly or indirectly to the largest number of subsequent patent families.[12] These subsequent families are divided into two groups, based on whether they are within or beyond wind energy technology. This highlights which WETO-funded patent families have been particularly influential within wind energy technology, and which have had a wider impact beyond wind energy.

Table 10 – Pre-2000 WETO-funded Wind Energy Patent Families Linked via Citations to Largest Number of Subsequent Wind Energy/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Wind Fams	Assignee	Title
24003638	1995	5798632	1052	685	MRIGlobal (NREL)	Variable speed wind turbine generator with zero-sequence filter
23382881	1982	4435646	770	654	Northern Power Systems	Wind turbine rotor control system
23152877	1981	4410806	666	589	US Dept Energy	Control system for a vertical axis windmill
25429916	1992	5320491	431	220	Northern Power Systems	Wind turbine rotor aileron
23640361	1982	4499034	349	142	US Dept Energy	Vortex-augmented cooling tower-windmill combination
25312016	1992	5354175	341	306	Northern Power Systems	Wind turbine rotor hub and teeter joint
24121765	1983	4504192	234	181	US Dept Energy	Jet spoiler arrangement for wind turbine
25523070	1997	6068446	232	186	MRIGlobal (NREL)	Airfoils for wind turbine
23863439	1983	4500257	230	191	US Dept Energy	Wind turbine spoiler

The patent family at the head of Table 10 (representative patent US #5,798,632) is the MRIGlobal variable speed wind turbine family highlighted above in both Table 5 and Table 9. This patent family is linked via citations to 1,052 subsequent patent families, 685 of which are within wind energy technology. The second patent family in Table 10 (representative patent US #4,435,646) was also highlighted earlier in the backward tracing element of the analysis. This family is assigned to Northern Power Systems, and describes wind turbine rotor control. It is

[12] The WETO-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.

linked via citations to 770 subsequent patent families, 654 from within wind energy. The third patent family in Table 10 (representative patent US #4,410,806) also has extensive citation links within wind energy, with 589 of the 666 patent families linked to it being related to this technology. This patent is assigned to DOE, and describes a vertical axis wind turbine. Indeed, one feature of Table 10 is that most of the patent families linked via citations to WETO-funded wind energy patents are themselves concerned with wind energy. This suggests that wind energy is a relatively self-contained technology, with successive generations of technology building on earlier innovations from within wind energy. A similar finding was reported earlier regarding the Cooperative Patent Classifications of patent families linked via citations to WETO-funded and Other DOE-funded wind energy patents (see Figure 18 and Figure 19).

Table 11 contains WETO-funded wind energy patent families with priority dates from 2000 onwards. That said, these families are all relatively old, dating from the start of this century. This table is headed by two Clipper Windpower patent families, the first of which (representative patent US #7,042,110) describes a variable speed wind turbine. This patent family is linked via citations to 737 subsequent families, 456 of them from within wind energy. The second Clipper patent family (representative patent US #7,233,129) describes wind turbine management in situations where there is an electrical fault. It is linked to 483 subsequent patent families, 305 of which are related to wind energy. Both of these Clipper patent families were highlighted earlier in the backward tracing element of the analysis (see Table 5). The patent family in third place in Table 11 (representative patent US #7,071,579) was granted in 2002 to Global Energy Concepts (subsequently acquired by DNV). This patent family describes variable speed wind turbines, and is linked via citations to 424 subsequent families, 259 of them related to wind energy. As in the case of Table 10, many of the citation links to the WETO-funded patent families in Table 11 are from within wind energy, again suggesting that this is a relatively self-contained technology.

Table 11 – Post-1999 WETO-funded Wind Energy Patent Families Linked via Citations to Largest Number of Subsequent Wind Energy/Other Patent Families

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Wind Fams	Assignee	Title
34679397	2003	7042110	737	456	Clipper Windpower	Variable speed distributed drive train wind turbine system
34681755	2003	7233129	483	305	Clipper Windpower	Generator with utility fault ride-through capability
29715422	2002	7071579	424	259	Global Energy Concepts	Wind farm electrical system
34966536	2004	7075192	391	306	Northern Power Syst	Direct drive wind turbine
35005063	2000	6951443	322	254	General Electric	Wind turbine ring/shroud drive system
34981372	2004	7309930	317	252	General Electric	Vibration damping system and method for variable speed wind turbines
34103166	2003	7004724	281	209	General Electric	Method and apparatus for wind turbine rotor load control based on shaft radial displacement
35455150	2004	7086834	243	198	General Electric	Methods and apparatus for rotor blade ice detection
24242945	2000	6503058	212	178	Zond Energy Systems	Air foil configuration for wind turbine

The tables above identify WETO-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 WETO-funded wind energy patents. As such, these are examples where WETO-funded wind energy research has formed part of the foundation for subsequent high-impact technologies. This table focuses on patent families not owned by the leading wind energy companies, since those families were examined in the backward tracing element of the analysis.

Table 12 - Highly Cited Patents (not from leading wind energy companies) Linked via Citations to Earlier WETO-funded Wind Energy Patents

Patent #	Issue Year	# Cites Received	Citation Index	Assignee	Title
9154024	2015	24	23.33	Boulder Wind Power	Systems and methods for improved direct drive generators
8350403	2013	38	13.21	Baseload Energy	Tether handling for airborne electricity generators
8140279	2012	54	9.16	Budderfly Ventures	Computer based energy management
8350397	2013	27	8.61	Rockwell Automation	Current source converter-based wind energy system
9207993	2015	24	8.27	Microsoft	Dynamic application placement based on cost and availability of energy in datacenters
4565929	1986	139	7.61	Boeing	Wind powered system for generating electricity
7804280	2010	47	5.75	Velatia Group	Method and system for providing power factor correction in a power distribution system
7656055	2010	59	5.61	Unassigned	Hydro-wind power generating turbine system and retrofitting method
7075189	2006	135	4.67	Ocean Wind Energy Systems	Offshore wind turbine with multiple wind rotors and floating system

The patent at the head of Table 12 (US #9,154,024) was granted in 2015 to Boulder Wind Power, a company founded by the ex-head of NREL's Wind Technology Center. This patent describes direct drive generators for wind turbines. It has been cited as prior art by 24 subsequent patents, while the expected number of citations for a patent of its age and technology is only slightly above one. The second patent in Table 12 (US #8,350,403) is assigned to Baseload Energy, and describes an airborne wind energy generation system. This patent has been cited as prior art by 38 subsequent patents since it was issued in 2013, more than thirteen times as many citations as expected. Table 12 also contains older highly-cited patents with links to earlier WETO-funded patents. For example, Boeing has a 1986 patent for a large-scale wind turbine (US #4,565,929) that has been cited by 139 subsequent patents, which is more than seven times as many citations as expected. In general, the patents in Table 11 are assigned to a variety of companies and describe a range of technologies related to wind energy, showing the breadth of influence of WETO-funded wind energy research on subsequent developments.

As with the backward tracing element of the analysis, the patent-level results from the forward tracing focus on WETO-funded wind energy patents. That said, within the forward tracing, we did also identify Other DOE-funded wind energy patent families linked to the largest number of subsequent patent families within and beyond wind energy technology. These Other DOE-funded wind energy families are shown in Table 13. Note that all of the patent families in this

table are marked as "unknown" in terms of their DOE funding source, rather than being definitely not WETO-funded. Hence, some of these patent families may in fact have been funded by WETO.

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

Family #	Priority Year	Rep. Patent #	# Linked Families	# Linked Wind Fams	Assignee	Title
24811296	1985	4651017	495	427	US Dept Energy	Wind energy conversion system
25406389	1978	4228391	432	148	US Dept Energy	Induction machine
24873660	1976	4083651	361	298	United Technologies	Wind turbine with automatic pitch and yaw control
22996301	1981	4366386	356	287	Windfree Inc	Magnus air turbine system
23459350	1995	5570859	341	222	Unassigned	Aerodynamic braking device
24765334	1985	4677364	337	66	US Dept Energy	Reactive power compensating system
23956360	1983	4452562	300	176	Iowa State Univ (Ames)	Tornado type wind turbines
23872115	1983	4482290	203	143	US Dept Energy	Diffuser for augmenting a wind turbine

The patent family at the head of Table 13 (representative patent US #4,651,017) is assigned to DOE and describes wind speed measurement for controlling wind turbines. This patent family was highlighted earlier in the backward tracing element of the analysis. It is linked via citations to 495 subsequent patent families, 427 of which are related to wind energy. The second patent family in Table 13 (representative patent US #4,228,391) is also assigned to DOE, and outlines induction machines for electricity generation, for example from wind turbines. This patent family is linked via citations 432 to subsequent families, only 148 of which are related to wind energy. Many of the remaining linked families are concerned with generators and motors in general, not necessarily limited to wind turbines. A similar pattern of citations can also be seen in another DOE patent family in Table 13 (representative patent US #4,677,364), which is also linked extensively via citations to subsequent patent families for generators and motors. Meanwhile, Table 13 also contains Other DOE-funded patent families with more extensive citation links within wind energy, notably families assigned to United Technologies (representative patent US #4,083,651) and Windfree (representative patent US #4,366,386).

Overall, the forward tracing element of the analysis shows that WETO-funded and Other DOE-funded wind energy research have had a strong influence on subsequent technologies. This influence can be seen most extensively within wind energy, but can also be traced in related technologies such as power distribution and electrical generators and motors.

5.0 Conclusions

This report describes the results of an analysis tracing links between wind energy research funded by DOE (WETO plus Other DOE) and subsequent developments both within and beyond wind energy 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 WETO-funded (and Other

DOE-funded) research forms a foundation for innovations associated with the leading wind energy companies. The purpose of the forward tracing is to examine the influence of WETO-funded (and Other DOE-funded) wind energy patents upon subsequent developments, both within and outside wind energy technology.

The backward tracing element of the analysis shows that, taking into account their relatively small size, the portfolios of WETO-funded and Other DOE-funded wind energy patents have had an important influence on subsequent innovations associated with the leading wind energy companies. This influence can be seen both over time and across wind energy technologies. Meanwhile, the forward tracing element of the analysis shows that WETO-funded and Other DOE-funded wind energy research has had a strong influence on subsequent developments, both within wind energy, and in related technologies such as power distribution and electrical generators and motors.

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

Appendix A. WETO-funded Wind Energy Patents used in the Analysis

Patent #	Application Year	Issue / Publication Year	Assignee	Title
4352629	1981	1982	UNITED TECHNOLOGIES CORP	WIND TURBINE
4410806	1981	1983	US DEPARTMENT OF ENERGY	CONTROL SYSTEM FOR A VERTICAL AXIS WINDMILL
4435646	1982	1984	NORTHERN POWER SYSTEMS INC	WIND TURBINE ROTOR CONTROL SYSTEM
4465537	1982	1984	NORTHERN POWER SYSTEMS INC	METHOD OF MAKING A WOODEN WIND TURBINE BLADE
4499034	1982	1985	US DEPARTMENT OF ENERGY	VORTEX-AUGMENTED COOLING TOWER-WINDMILL COMBINATION
4500257	1983	1985	US DEPARTMENT OF ENERGY	WIND TURBINE SPOILER
4504192	1983	1985	US DEPARTMENT OF ENERGY	JET SPOILER ARRANGEMENT FOR WIND TURBINE
4545728	1983	1985	UNASSIGNED	WIND TURBINE GENERATOR WITH IMPROVED OPERATING SUBASSEMBLIES
4597715	1984	1986	NORTHERN POWER SYSTEMS INC	WOODEN WIND TURBINE BLADE MANUFACTURING PROCESS
5320491	1992	1994	NORTHERN POWER SYSTEMS INC	WIND TURBINE ROTOR AILERON
5354175	1993	1994	NORTHERN POWER SYSTEMS INC	WIND TURBINE ROTOR HUB AND TEETER JOINT
WO1994001325	1993	1994	NORTHERN POWER SYSTEMS INC	WIND TURBINE ROTOR AILERON
5417548	1994	1995	MIDWEST RESEARCH INSTITUTE	ROOT REGION AIRFOIL FOR WIND TURBINE
EP0663527	1994	1995	MIDWEST RESEARCH INSTITUTE	ROOT REGION AIRFOIL FOR WIND TURBINE.
EP0675285	1995	1995	MIDWEST RESEARCH INSTITUTE	AIRFOILS FOR WIND TURBINE.
5527151	1992	1996	NORTHERN POWER SYSTEMS INC	ADVANCED WIND TURBINE WITH LIFT-DESTROYING AILERON FOR SHUTDOWN
5527152	1994	1996	NORTHERN POWER SYSTEMS INC	ADVANCED WIND TURBINE WITH LIFT CANCELLING AILERON FOR SHUTDOWN
5562420	1994	1996	MIDWEST RESEARCH INSTITUTE	AIRFOILS FOR WIND TURBINE
WO1997004521	1996	1997	MIDWEST RESEARCH INSTITUTE	A VARIABLE SPEED WIND TURBINE GENERATOR SYSTEM WITH ZERO-SEQUENCE FILTER
5798632	1997	1998	MIDWEST RESEARCH	VARIABLE SPEED WIND

			INSTITUTE	TURBINE GENERATOR WITH ZERO-SEQUENCE FILTER
WO1999027252	1998	1999	MIDWEST RESEARCH INSTITUTE	AIRFOILS FOR WIND TURBINE
6068446	1997	2000	MIDWEST RESEARCH INSTITUTE	AIRFOILS FOR WIND TURBINE
EP1152148	2001	2001	ZOND ENERGY SYSTEMS INC	AIRFOIL PROFILES FOR WIND TURBINES
WO2001083983	2001	2001	ZOND ENERGY SYSTEMS INC	AIR FOIL CONFIGURATION FOR WIND TURBINE
6503058	2000	2003	ZOND ENERGY SYSTEMS INC	AIR FOIL CONFIGURATION FOR WIND TURBINE
6731017	2002	2004	CLIPPER WINDPOWER TECHNOLOGY INC	DISTRIBUTED POWERTRAIN THAT INCREASES ELECTRIC POWER GENERATOR DENSITY
6900998	2003	2005	MIDWEST RESEARCH INSTITUTE	VARIABLE-SPEED WIND POWER SYSTEM WITH IMPROVED ENERGY CAPTURE VIA MULTILEVEL CONVERSION
6951443	2000	2005	GENERAL ELECTRIC CO	WIND TURBINE RING/SHROUD DRIVE SYSTEM
6954004	2003	2005	SPELLMAN HIGH VOLTAGE ELECTRONICS CORP	DOUBLY FED INDUCTION MACHINE
6972498	2002	2005	GENERAL ELECTRIC CO	VARIABLE DIAMETER WIND TURBINE ROTOR BLADES
EP1561945	2005	2005	CLIPPER WINDPOWER TECHNOLOGY INC	VARIABLE SPEED DISTRIBUTED DRIVE TRAIN WIND TURBINE SYSTEM
EP1561946	2005	2005	CLIPPER WINDPOWER TECHNOLOGY INC	GENERATOR WITH UTILITY FAULT RIDE-THROUGH CAPABILITY
WO2005010358	2004	2005	GENERAL ELECTRIC CO	METHOD AND APPARATUS FOR WIND TURBINE ROTOR LOAD CONTROL BASED ON SHAFT RADIAL DISPLACEMENT
WO2005081995	2005	2005	3-TEX INC	WIND BLADE SPAR CAP AND METHOD OF MAKING
WO2005103489	2005	2005	NORTHERN POWER SYSTEMS INC	DIRECT DRIVE WIND TURBINE
6984897	2003	2006	SPELLMAN HIGH VOLTAGE ELECTRONICS CORP	ELECTRO-MECHANICAL ENERGY CONVERSION SYSTEM HAVING A PERMANENT MAGNET MACHINE WITH STATOR, RESONANT TRANSFER LINK AND ENERGY

				CONVERTER CONTROLS
7002259	2002	2006	CLIPPER WINDPOWER TECHNOLOGY INC	METHOD OF CONTROLLING ELECTRICAL ROTATING MACHINES CONNECTED TO A COMMON SHAFT
7004724	2003	2006	GENERAL ELECTRIC CO	METHOD AND APPARATUS FOR WIND TURBINE ROTOR LOAD CONTROL BASED ON SHAFT RADIAL DISPLACEMENT
7042110	2004	2006	CLIPPER WINDPOWER TECHNOLOGY INC	VARIABLE SPEED DISTRIBUTED DRIVE TRAIN WIND TURBINE SYSTEM
7071579	2003	2006	GLOBAL ENERGY CONCEPTS, INC.	WIND FARM ELECTRICAL SYSTEM
7075192	2004	2006	NORTHERN POWER SYSTEMS INC	DIRECT DRIVE WIND TURBINE
7086834	2004	2006	GENERAL ELECTRIC CO	METHODS AND APPARATUS FOR ROTOR BLADE ICE DETECTION
7095129	2004	2006	GENERAL ELECTRIC CO	METHODS AND APPARATUS FOR ROTOR LOAD CONTROL IN WIND TURBINES
7095597	2003	2006	CLIPPER WINDPOWER TECHNOLOGY INC	DISTRIBUTED STATIC VAR COMPENSATION (DSVC) SYSTEM FOR WIND AND WATER TURBINE APPLICATIONS
7109600	2006	2006	NORTHERN POWER SYSTEMS INC	DIRECT DRIVE WIND TURBINE
7118338	2004	2006	GENERAL ELECTRIC CO	METHODS AND APPARATUS FOR TWIST BEND COUPLED (TCB) WIND TURBINE BLADES
7118339	2004	2006	GENERAL ELECTRIC CO	METHODS AND APPARATUS FOR REDUCTION OF ASYMMETRIC ROTOR LOADS IN WIND TURBINES
7119453	2006	2006	NORTHERN POWER SYSTEMS INC	DIRECT DRIVE WIND TURBINE
7121795	2004	2006	GENERAL ELECTRIC CO	METHOD AND APPARATUS FOR REDUCING ROTOR BLADE DEFLECTIONS, LOADS, AND/OR PEAK ROTATIONAL SPEED
EP1612413	2005	2006	GENERAL ELECTRIC CO	METHODS AND APPARATUS FOR REDUCTION OF ASYMMETRIC ROTOR LOADS IN WIND TURBINES
EP1612414	2005	2006	GENERAL ELECTRIC CO	METHOD AND APPARATUS FOR REDUCING ROTOR

				BLADE DEFLECTIONS, LOADS AND/OR PEAK ROTATIONAL SPEED
EP1643122	2005	2006	GENERAL ELECTRIC CO	VIBRATION DAMPING SYSTEM AND METHOD FOR VARIABLE SPEED WIND TURBINES
EP1646786	2004	2006	GENERAL ELECTRIC CO	METHOD AND APPARATUS FOR WIND TURBINE ROTOR LOAD CONTROL BASED ON SHAFT RADIAL DISPLACEMENT
WO2006093790	2006	2006	UNASSIGNED	WIND FIN: ARTICULATED, OSCILLATING WIND POWER GENERATOR
WO2006125118	2006	2006	UNIVERSITY OF CALIFORNIA	VERTICAL AXIS WIND TURBINES
7160083	2003	2007	GENERAL ELECTRIC CO	METHOD AND APPARATUS FOR WIND TURBINE ROTOR LOAD CONTROL
7175389	2004	2007	GENERAL ELECTRIC CO	METHODS AND APPARATUS FOR REDUCING PEAK WIND TURBINE LOADS
7180204	2005	2007	GENERAL ELECTRIC CO	METHOD AND APPARATUS FOR WIND TURBINE AIR GAP CONTROL
7183665	2006	2007	NORTHERN POWER SYSTEMS INC	DIRECT DRIVE WIND TURBINE
7233129	2004	2007	CLIPPER WINDPOWER TECHNOLOGY INC	GENERATOR WITH UTILITY FAULT RIDE-THROUGH CAPABILITY
7309930	2004	2007	GENERAL ELECTRIC CO	VIBRATION DAMPING SYSTEM AND METHOD FOR VARIABLE SPEED WIND TURBINES
EP1760311	2006	2007	GENERAL ELECTRIC CO	METHOD AND APPARATUS FOR CONDITION-BASED MONITORING OF WIND TURBINE COMPONENTS
EP1770278	2006	2007	GENERAL ELECTRIC CO	SYSTEM AND METHOD FOR CONTROL OF A WIND TURBINE BASED ON MEASURED WIND SPEED UPSTREAM
EP1772624	2006	2007	GENERAL ELECTRIC CO	DIRECT-DIRVE WIND TURBINE ELECTRIC GENERATOR WITH REMOVABLE BEARING ARRANGEMENT
EP1775466	2006	2007	GENERAL ELECTRIC CO	WIND TURBINE TOWER AND METHOD FOR CONSTRUCTING THE SAME
EP1788237	2006	2007	GENERAL ELECTRIC CO	METHOD AND APPARATUS FOR WIND TURBINE BRAKING

EP1837519	2007	2007	GENERAL ELECTRIC CO	WIND TURBINE GENERATORS HAVING WIND ASSISTED COOLING SYSTEMS AND COOLING METHODS
EP1870566	2007	2007	GENERAL ELECTRIC CO	METHODS AND APPARATUS FOR CONTROLLING ROTARY MACHINES
WO2007123552	2006	2007	ALLIANCE FOR SUSTAINABLE ENERGY LLC	ADAPTIVE PITCH CONTROL FOR VARIABLE SPEED WIND TURBINES
7322794	2005	2008	GENERAL ELECTRIC CO	METHOD AND APPARATUS FOR CONDITION-BASED MONITORING OF WIND TURBINE COMPONENTS
7339355	2007	2008	CLIPPER WINDPOWER TECHNOLOGY INC	GENERATOR WITH UTILITY FAULT RIDE-THROUGH CAPABILITY
7342323	2005	2008	GENERAL ELECTRIC CO	SYSTEM AND METHOD FOR UPWIND SPEED BASED CONTROL OF A WIND TURBINE
7344360	2004	2008	GENERAL ELECTRIC CO	WIND TURBINE ROTOR BLADE WITH IN-PLANE SWEEP AND DEVICES USING SAME, AND METHODS FOR MAKING SAME
7345376	2005	2008	DISTRIBUTED ENERGY SYSTEMS CORP	PASSIVELY COOLED DIRECT DRIVE WIND TURBINE
7351040	2006	2008	GENERAL ELECTRIC CO	METHODS OF MAKING WIND TURBINE ROTOR BLADES
7360310	2005	2008	GENERAL ELECTRIC CO	METHOD FOR CHANGING REMOVABLE BEARING FOR A WIND TURBINE GENERATOR
7377750	2005	2008	NORTHERN POWER SYSTEMS INC	LIGHTNING PROTECTION SYSTEM FOR A WIND TURBINE
7377752	2006	2008	3-TEX INC	WIND BLADE SPAR CAP AND METHOD OF MAKING
7381029	2004	2008	GENERAL ELECTRIC CO	MULTI-PIECE WIND TURBINE ROTOR BLADES AND WIND TURBINES INCORPORATING SAME
7391126	2006	2008	GENERAL ELECTRIC CO	SYSTEMS AND METHODS FOR AN INTEGRATED ELECTRICAL SUB-SYSTEM POWERED BY WIND ENERGY
7423352	2007	2008	GENERAL ELECTRIC CO	VIBRATION DAMPING METHOD FOR VARIABLE SPEED WIND TURBINES

7427814	2006	2008	GENERAL ELECTRIC CO	WIND TURBINE GENERATORS HAVING WIND ASSISTED COOLING SYSTEMS AND COOLING METHODS
7431567	2004	2008	NORTHERN POWER SYSTEMS INC	WIND TURBINE HAVING A DIRECT-DRIVE DRIVETRAIN
7432686	2007	2008	CLIPPER WINDPOWER TECHNOLOGY INC	WIND TURBINE GENERATOR APPARATUS WITH UTILITY FAULT RIDE-THROUGH CAPABILITY
7443066	2005	2008	GENERAL ELECTRIC CO	METHODS AND APPARATUS FOR COOLING WIND TURBINE GENERATORS
7471010	2004	2008	ALLIANCE FOR SUSTAINABLE ENERGY LLC	WIND TURBINE TOWER FOR STORING HYDROGEN AND ENERGY
EP1873888	2007	2008	GENERAL ELECTRIC CO	ELECTRICAL MACHINE WITH IMPROVED WINDING
EP1888917	2006	2008	UNIVERSITY OF CALIFORNIA	VERTICAL AXIS WIND TURBINE HAVING AN OVERSPEEDING REGULATOR CONTROLLING MULTIPLE AERODYNAMIC ELEMENTS
EP1922482	2006	2008	UNASSIGNED	WIND FIN: ARTICULATED, OSCILLATING WIND POWER GENERATOR
7488155	2005	2009	GENERAL ELECTRIC CO	METHOD AND APPARATUS FOR WIND TURBINE BRAKING
7521835	2006	2009	GENERAL ELECTRIC CO	PERMANENT MAGNET MACHINE WITH WINDINGS HAVING STRAND TRANSPOSITION
7530785	2005	2009	THE WIND TURBINE CO	METHOD AND APPARATUS FOR CONTROLLING PITCH AND FLAP ANGLES OF A WIND TURBINE
7535120	2007	2009	CLIPPER WINDPOWER TECHNOLOGY INC	POWER SYSTEM WITH LOW VOLTAGE RIDE-THROUGH CAPABILITY
7581921	2006	2009	GENERAL ELECTRIC CO	METHODS AND APPARATUS FOR CONTROLLING ROTARY MACHINES
EP2035899	2006	2009	ALLIANCE FOR SUSTAINABLE ENERGY LLC	ADAPTIVE PITCH CONTROL FOR VARIABLE SPEED WIND TURBINES
EP2096300	2009	2009	GENERAL ELECTRIC CO	METHOD OF CONTROLLING THE TIP SPEED RATIO OF WIND

				TURBINE BLADES
EP2114007	2005	2009	CLIPPER WINDPOWER TECHNOLOGY INC	POWER-SYSTEM WITH UTILITY FAULT RIDE-THROUGH CAPABILITY
WO2009062159	2008	2009	ALLIANCE FOR SUSTAINABLE ENERGY LLC	QUIET AIRFOILS FOR SMALL AND LARGE WIND TURBINES
WO2009097049	2008	2009	ALLIANCE FOR SUSTAINABLE ENERGY LLC	DUAL-AXIS RESONANCE TESTING OF WIND TURBINE BLADES
WO2009097055	2008	2009	ALLIANCE FOR SUSTAINABLE ENERGY LLC	WIND TURBINE BLADE TESTING SYSTEM USING BASE EXCITATION
WO2009135136	2009	2009	ALLIANCE FOR SUSTAINABLE ENERGY LLC	BASE EXCITATION TESTING SYSTEM USING SPRING ELEMENTS TO PIVOTALLY MOUNT WIND TURBINE BLADES
WO2009138827	2009	2009	CLIPPER WINDPOWER TECHNOLOGY INC	FLEXIBLE PIN FOR HELICAL GEARS
7692357	2004	2010	GENERAL ELECTRIC CO	ELECTRICAL MACHINES AND ASSEMBLIES INCLUDING A YOKELESS STATOR WITH MODULAR LAMINATION STACKS
7735290	2005	2010	GENERAL ELECTRIC CO	WIND TURBINE ASSEMBLY TOWER
7736125	2008	2010	GENERAL ELECTRIC CO	REMOVABLE BEARING ARRANGEMENT FOR A WIND TURBINE GENERATOR
EP2150725	2009	2010	CLIPPER WINDPOWER TECHNOLOGY INC	FLEXIBLE PIN FOR HELICAL GEARS
7891941	2008	2011	NORTHERN POWER SYSTEMS INC	WIND TURBINE HAVING A DIRECT-DRIVE DRIVETRAIN
7902688	2007	2011	UNIVERSITY OF CALIFORNIA	VERTICAL AXIS WIND TURBINES
7976282	2007	2011	GENERAL ELECTRIC CO	PREFORM SPAR CAP FOR A WIND TURBINE ROTOR BLADE
EP2273107	2005	2011	CLIPPER WINDPOWER TECHNOLOGY INC	VARIABLE SPEED DISTRIBUTED DRIVE TRAIN WIND TURBINE SYSTEM
WO2011084530	2010	2011	CLEAR PATH ENERGY LLC	FLOATING UNDERWATER SUPPORT STRUCTURE
WO2011084544	2010	2011	CLEAR PATH ENERGY LLC	AXIAL GAP ROTATING ELECTRICAL MACHINE
8113986	2009	2012	CLIPPER WINDPOWER TECHNOLOGY INC	FLEXIBLE PIN FOR HELICAL GEARS
8161698	2008	2012	ANEMERGONICS LLC	FOUNDATION FOR MONOPOLE WIND

				TURBINE TOWER
8174136	2006	2012	ALLIANCE FOR SUSTAINABLE ENERGY LLC	ADAPTIVE PITCH CONTROL FOR VARIABLE SPEED WIND TURBINES
8197208	2010	2012	CLEAR PATH ENERGY LLC	FLOATING UNDERWATER SUPPORT STRUCTURE
8197218	2007	2012	ALLIANCE FOR SUSTAINABLE ENERGY LLC	QUIET AIRFOILS FOR SMALL AND LARGE WIND TURBINES
8215906	2008	2012	GENERAL ELECTRIC CO	VARIABLE TIP SPEED RATIO TRACKING CONTROL FOR WIND TURBINES
8251657	2011	2012	SIEMENS AG	LOAD MITIGATION DEVICE FOR WIND TURBINE BLADES
8308430	2011	2012	NORTHERN POWER SYSTEMS INC	WIND TURBINE/GENERATOR SET HAVING A STATOR COOLING SYSTEM LOCATED BETWEEN STATOR FRAME AND ACTIVE COILS
8333564	2011	2012	UNIVERSITY OF CALIFORNIA	VERTICAL AXIS WIND TURBINE AIRFOIL
WO2012061710	2011	2012	UNIVERSITY OF MAINE	FLOATING HYBRID COMPOSITE WIND TURBINE PLATFORM AND TOWER SYSTEM
WO2012093022	2011	2012	SIEMENS AG	LOAD MITIGATION DEVICE FOR WIND TURBINE BLADES
8373299	2010	2013	CLEAR PATH ENERGY LLC	AXIAL GAP ROTATING ELECTRICAL MACHINE
8454309	2011	2013	NORTHERN POWER SYSTEMS INC	WIND TURBINE/GENERATOR SET AND METHOD OF MAKING SAME
8601878	2009	2013	ALLIANCE FOR SUSTAINABLE ENERGY LLC	BASE EXCITATION TESTING SYSTEM USING SPRING ELEMENTS TO PIVOTALLY MOUNT WIND TURBINE BLADES
EP2587051	2006	2013	UNIVERSITY OF CALIFORNIA	VERTICAL AXIS WIND TURBINES
EP2592265	2012	2013	SIEMENS AG	POWER PRODUCING SPINNER FOR A WIND TURBINE
EP2606226	2011	2013	SIEMENS AG	LOAD MITIGATION DEVICE FOR WIND TURBINE BLADES
EP2635489	2011	2013	UNIVERSITY OF MAINE	FLOATING HYBRID COMPOSITE WIND TURBINE PLATFORM AND TOWER SYSTEM
EP2647836	2013	2013	SIEMENS AG	SLAT WITH TIP VORTEX

				MODIFICATION APPENDAGE FOR WIND TURBINE
WO2013110527	2013	2013	SIEMENS AG	WIND TURBINE BLADE HAVING A GEOMETRIC SWEEP
8621934	2008	2014	ALLIANCE FOR SUSTAINABLE ENERGY LLC	DUAL-AXIS RESONANCE TESTING OF WIND TURBINE BLADES
8649911	2005	2014	GENERAL ELECTRIC CO	SYSTEM AND METHOD FOR OPERATING A WIND FARM UNDER HIGH WIND SPEED CONDITIONS
8657575	2007	2014	UNASSIGNED	OSCILLATING FLUID POWER GENERATOR
8677827	2008	2014	ALLIANCE FOR SUSTAINABLE ENERGY LLC	WIND TURBINE BLADE TESTING SYSTEM USING BASE EXCITATION
8757982	2008	2014	GENERAL ELECTRIC CO	WIND TURBINE ROTOR BLADE WITH IN-PLANE SWEEP AND DEVICES USING SAME, AND METHODS FOR MAKING SAME
8860236	2010	2014	UWM RESEARCH FOUNDATION INC	WIND ENERGY POWER CONVERSION SYSTEM REDUCING GEARBOX STRESS AND IMPROVING POWER STABILITY
EP2761170	2013	2014	SIEMENS AG	WIND TURBINE BLADE HAVING A GEOMETRIC SWEEP
EP2767710	2013	2014	SIEMENS AG	METHOD AND SYSTEM FOR IMPROVING WIND FARM POWER PRODUCTION EFFICIENCY
WO2014018956	2013	2014	TEXAS TECH UNIVERSITY	SYSTEM AND METHOD FOR EVALUATING WIND FLOW FIELDS USING REMOTE SENSING DEVICES
WO2014018957	2013	2014	TEXAS TECH UNIVERSITY	APPARATUS AND METHOD FOR USING RADAR TO EVALUATE WIND FLOW FIELDS FOR WIND ENERGY APPLICATIONS
8985947	2011	2015	SIEMENS AG	POWER PRODUCING SPINNER FOR A WIND TURBINE
9062662	2014	2015	EBERT COMPOSITES CORP	HYBRID POLE STRUCTURE AND METHOD OF ASSEMBLY
9175666	2012	2015	SIEMENS AG	SLAT WITH TIP VORTEX MODIFICATION APPENDAGE FOR WIND TURBINE

9188677	2014	2015	SANDIA CORP	IMAGING DOPPLER LIDAR FOR WIND TURBINE WAKE PROFILING
EP2877741	2013	2015	TEXAS TECH UNIVERSITY	SYSTEM AND METHOD FOR EVALUATING WIND FLOW FIELDS USING REMOTE SENSING DEVICES
EP2877875	2013	2015	TEXAS TECH UNIVERSITY	APPARATUS AND METHOD FOR USING RADAR TO EVALUATE WIND FLOW FIELDS FOR WIND ENERGY APPLICATIONS
EP2915996	2015	2015	SIEMENS AG	WIND TURBINE BLADE WITH VISCOELASTIC DAMPING
EP2933475	2015	2015	SIEMENS AG	VORTEX GENERATORS ALIGNED WITH TRAILING EDGE FEATURES ON WIND TURBINE BLADE
WO2015084790	2014	2015	HYPER TECH RESEARCH INC	SUPERCONDUCTING GENERATORS AND MOTORS
9240681	2012	2016	GENERAL ELECTRIC CO	SUPERCONDUCTING COIL SYSTEM AND METHODS OF ASSEMBLING THE SAME
9267490	2012	2016	SANDIA CORP	AEROELASTICALLY COUPLED BLADES FOR VERTICAL AXIS WIND TURBINES
9270150	2013	2016	CLEAR PATH ENERGY LLC	AXIAL GAP ROTATING ELECTRICAL MACHINE
9394035	2013	2016	UNIVERSITY OF MAINE	FLOATING WIND TURBINE PLATFORM AND METHOD OF ASSEMBLING
9404371	2013	2016	SANDIA CORP	REDUCTION OF RADAR CROSS-SECTION OF A WIND TURBINE
9476406	2014	2016	SIEMENS AG	VORTEX GENERATORS ALIGNED WITH TRAILING EDGE FEATURES ON WIND TURBINE BLADE
9512820	2013	2016	SIEMENS AG	METHOD AND SYSTEM FOR IMPROVING WIND FARM POWER PRODUCTION EFFICIENCY
9518564	2011	2016	UNIVERSITY OF MAINE	FLOATING HYBRID COMPOSITE WIND TURBINE PLATFORM AND TOWER SYSTEM
9519056	2013	2016	TEXAS TECH UNIVERSITY	SYSTEM AND METHOD FOR EVALUATING WIND FLOW FIELDS USING REMOTE SENSING DEVICES

9541061	2014	2017	SIEMENS AG	WIND TURBINE BLADE WITH VISCOELASTIC DAMPING
9570220	2012	2017	GENERAL ELECTRIC CO	REMOTE ACTUATED CRYOCOOLER FOR SUPERCONDUCTING GENERATOR AND METHOD OF ASSEMBLING THE SAME
9575177	2013	2017	TEXAS TECH UNIVERSITY	APPARATUS AND METHOD FOR USING RADAR TO EVALUATE WIND FLOW FIELDS FOR WIND ENERGY APPLICATIONS
9651629	2013	2017	CLEMSON UNIVERSITY	HARDWARE-IN-THE-LOOP GRID SIMULATOR SYSTEM AND METHOD
9702346	2013	2017	HONEYWELL INTERNATIONAL INC	SYNCHRONIZING DATA FROM IRREGULARLY SAMPLED SENSORS
9748820	2014	2017	HYPER TECH RESEARCH INC	SUPERCONDUCTING GENERATORS AND MOTORS AND METHODS FOR EMPLOYING SAME
WO2017039666	2015	2017	SIEMENS AG	WIND TURBINE BLADE WITH TRAILING EDGE TAB
9920741	2012	2018	SIEMENS AG	WIND TURBINE BLADE HAVING A GEOMETRIC SWEEP
10077955	2015	2018	KATO ENGINEERING INC	SUPERCONDUCTING ELECTRICAL MACHINE WITH DOUBLE RE-ENTRANT ENDS FOR MINIMIZING HEAT LEAK
10079534	2015	2018	KATO ENGINEERING INC	SUPERCONDUCTING ELECTRICAL MACHINE WITH ROTOR AND STATOR HAVING SEPARATE CRYOSTATS
EP3329117	2015	2018	SIEMENS AG	WIND TURBINE BLADE WITH TRAILING EDGE TAB
10270311	2015	2019	KATO ENGINEERING INC	SUPERCONDUCTING ELECTRICAL MACHINE WITH TWO PART ROTOR WITH CENTER SHAFT CAPABLE OF HANDLING BENDING LOADS
10495056	2015	2019	SIEMENS AG	WIND TURBINE BLADE WITH TRAILING EDGE TAB
10598155	2016	2020	UNIVERSITY OF MAINE	FLOATING HYBRID COMPOSITE WIND TURBINE PLATFORM AND TOWER SYSTEM WITH SUSPENDED MASS

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

Patent #	Application Year	Issue / Publication Year	Assignee	Title
4083651	1976	1978	UNITED TECHNOLOGIES CORP	WIND TURBINE WITH AUTOMATIC PITCH AND YAW CONTROL
4228391	1978	1980	US DEPARTMENT OF ENERGY	INDUCTION MACHINE
4366386	1981	1982	WINDFREE INC	MAGNUS AIR TURBINE SYSTEM
4392785	1980	1983	UNASSIGNED	PUMP CONTROL SYSTEM FOR WINDMILLS
4452562	1983	1984	IOWA STATE UNIVERSITY	TORNADO TYPE WIND TURBINES
4482290	1983	1984	US DEPARTMENT OF ENERGY	DIFFUSER FOR AUGMENTING A WIND TURBINE
4651017	1985	1987	US DEPARTMENT OF ENERGY	WIND ENERGY CONVERSION SYSTEM
4677364	1985	1987	US DEPARTMENT OF ENERGY	REACTIVE POWER COMPENSATING SYSTEM
4718825	1986	1988	UNASSIGNED	ACTIVE CONTROL SYSTEM FOR HIGH SPEED WINDMILLS
5570859	1995	1996	UNASSIGNED	AERODYNAMIC BRAKING DEVICE
7239044	2004	2007	SANDIA CORP	ENHANCED DISTRIBUTED ENERGY RESOURCE SYSTEM
WO2007092106	2007	2007	WIND TOWER SYSTEMS LLC	LIFTING SYSTEM AND APPARATUS FOR CONSTRUCTING WIND TURBINE TOWERS
7385330	2007	2008	UNIVERSITY OF NEVADA RENO	PERMANENT-MAGNET SWITCHED-FLUX MACHINE
EP1933441	2007	2008	GENERAL ELECTRIC CO	SYSTEM AND METHOD FOR CONTROLLING A MICROGRID
EP1974111	2007	2008	WIND TOWER SYSTEMS LLC	LIFTING SYSTEM AND APPARATUS FOR CONSTRUCTING WIND TURBINE TOWERS
WO2008109265	2008	2008	WISCONSIN ALUMNI RESEARCH FOUNDATION	INVERTER BASED STORAGE IN DYNAMIC DISTRIBUTION SYSTEMS INCLUDING DISTRIBUTED ENERGY RESOURCES
EP2132852	2008	2009	WISCONSIN ALUMNI RESEARCH FOUNDATION	INVERTER BASED STORAGE IN DYNAMIC DISTRIBUTION SYSTEMS INCLUDING DISTRIBUTED ENERGY RESOURCES
WO2009103020	2009	2009	ALLIANCE FOR SUSTAINABLE	RENEWABLE ENERGY DELIVERY SYSTEMS AND

			ENERGY LLC	METHODS
WO2009140435	2009	2009	PURDUE RESEARCH FOUNDATION	MONITORING OF WIND TURBINES
WO2009146451	2009	2009	WIND TOWER SYSTEMS LLC	WIND TOWER SERVICE LIFT
7646126	2008	2010	UNIVERSITY OF NEVADA RENO	PERMANENT-MAGNET SWITCHED-FLUX MACHINE
7646132	2007	2010	EMPIRE MAGNETICS INC	ARCUATE COIL WINDING AND ASSEMBLY FOR AXIAL GAP ELECTRO-DYNAMO MACHINES (EDM)
7787272	2007	2010	WISCONSIN ALUMNI RESEARCH FOUNDATION	INVERTER BASED STORAGE IN DYNAMIC DISTRIBUTION SYSTEMS INCLUDING DISTRIBUTED ENERGY RESOURCES
EP2201825	2008	2010	EMPIRE MAGNETICS INC	ARCUATE COIL WINDING FOR EDM
WO2010075117	2009	2010	GENERAL ELECTRIC CO	STRUCTURAL SHAPE FOR WIND TOWER MEMBERS
7877934	2007	2011	WIND TOWER SYSTEMS LLC	LIFTING SYSTEM AND APPARATUS FOR CONSTRUCTING WIND TURBINE TOWERS
7953563	2008	2011	LOS ALAMOS NATIONAL SECURITY LLC	DETERMINING EFFECTS OF TURBINE BLADES ON FLUID MOTION
7960887	2010	2011	UNIVERSITY OF NEVADA RENO	PERMANENT-MAGNET SWITCHED-FLUX MACHINE
7983799	2006	2011	GENERAL ELECTRIC CO	SYSTEM AND METHOD FOR CONTROLLING MICROGRID
8016268	2008	2011	WIND TOWER SYSTEMS LLC	WIND TOWER SERVICE LIFT
EP2280138	2007	2011	WIND TOWER SYSTEMS LLC	LIFTING SYSTEM AND APPARATUS FOR CONSTRUCTING WIND TURBINE TOWERS
EP2288808	2009	2011	PURDUE RESEARCH FOUNDATION	MONITORING OF WIND TURBINES
EP2300346	2009	2011	WIND TOWER SYSTEMS LLC	WIND TOWER SERVICE LIFT
EP2376726	2009	2011	GENERAL ELECTRIC CO	STRUCTURAL SHAPE FOR WIND TOWER MEMBERS
8120224	2011	2012	UNIVERSITY OF NEVADA RENO	PERMANENT-MAGNET SWITCHED-FLUX MACHINE
8170813	2011	2012	LOS ALAMOS NATIONAL SECURITY LLC	DETERMINING EFFECTS OF TURBINE BLADES ON FLUID MOTION
8261429	2009	2012	EMPIRE	ARCUATE COIL WINDING

			MAGNETICS INC	AND ASSEMBLY FOR AXIAL GAP ELECTRO-DYNAMO MACHINES (EDM)
WO2012078433	2011	2012	SANDIA CORP	COMPUTING ARCHITECTURE FOR AUTONOMOUS MICROGRIDS
8545657	2009	2013	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	METHODS FOR TAPE FABRICATION OF CONTINUOUS FILAMENT COMPOSITE PARTS AND ARTICLES OF MANUFACTURE THEREOF
8604641	2009	2013	ALLIANCE FOR SUSTAINABLE ENERGY LLC	RENEWABLE ENERGY DELIVERY SYSTEMS AND METHODS
WO2013019352	2012	2013	SIEMENS AKTIENGESELLSCHAFT	TURBINE AIRFOIL TO SHROUD ATTACHMENT METHOD
WO2013059376	2012	2013	KOHANA TECHNOLOGIES INC	TURBINE BLADES AND SYSTEMS WITH FORWARD BLOWING SLOTS
8910446	2009	2014	GENERAL ELECTRIC CO	STRUCTURAL SHAPE FOR WIND TOWER MEMBERS
8914976	2011	2014	SIEMENS AKTIENGESELLSCHAFT	TURBINE AIRFOIL TO SHROUD ATTACHMENT METHOD
EP2739415	2012	2014	SIEMENS AKTIENGESELLSCHAFT	TURBINE AIRFOIL TO SHROUD ATTACHMENT METHOD
EP2769092	2012	2014	KOHANA TECHNOLOGIES INC	TURBINE BLADES AND SYSTEMS WITH FORWARD BLOWING SLOTS
EP2779350	2014	2014	GENERAL ELECTRIC CO	DIRECT CURRENT TRANSMISSION AND DISTRIBUTION SYSTEM AND METHOD OF OPERATING THE SAME
9121288	2012	2015	SIEMENS AKTIENGESELLSCHAFT	TURBINE BLADE WITH TUNED DAMPING STRUCTURE
9133819	2012	2015	KOHANA TECHNOLOGIES INC	TURBINE BLADES AND SYSTEMS WITH FORWARD BLOWING SLOTS
9148019	2011	2015	SANDIA CORP	COMPUTING ARCHITECTURE FOR AUTONOMOUS MICROGRIDS
EP2854280	2014	2015	GENERAL ELECTRIC CO	HIGH VOLTAGE DC POWER CONVERSION SYSTEM AND METHOD OF OPERATING THE SAME
EP2921289	2015	2015	GENERAL ELECTRIC CO	SYSTEM AND METHOD FOR MANUFACTURE OF AIRFOIL COMPONENTS

WO2008137398	2008	2015	EMPIRE MAGNETICS INC	ARCUATE COIL WINDING FOR EDM
9306391	2013	2016	GENERAL ELECTRIC CO	DIRECT CURRENT TRANSMISSION AND DISTRIBUTION SYSTEM AND METHOD OF OPERATING THE SAME
9375894	2013	2016	LAWRENCE LIVERMORE NATIONAL SECURITY LLC	CONTINUOUS FILAMENT COMPOSITE PARTS AND ARTICLES OF MANUFACTURE THEREOF
9407157	2013	2016	GENERAL ELECTRIC CO	HIGH VOLTAGE DC POWER CONVERSION SYSTEM AND METHOD OF OPERATING THE SAME
9505182	2014	2016	GENERAL ELECTRIC CO	SYSTEM AND METHOD FOR MANUFACTURE OF AIRFOIL COMPONENTS
9651024	2014	2017	GENERAL ELECTRIC CO	ROTOR BLADE ASSEMBLY HAVING INTERNAL LOADING FEATURES
9714085	2009	2017	PURDUE RESEARCH FOUNDATION	MONITORING OF WIND TURBINES
10006436	2014	2018	GENERAL ELECTRIC CO	WIND TURBINE ROTOR BLADES WITH LOAD-TRANSFERRING EXTERIOR PANELS
10024300	2015	2018	KOHANA TECHNOLOGIES INC	TURBINE BLADES AND SYSTEMS WITH FORWARD BLOWING SLOTS
10148092	2017	2018	ALLIANCE FOR SUSTAINABLE ENERGY LLC, UNIVERSITY OF MINNESOTA, TECHNISCHE UNIVERSITEIT DELFT	REAL TIME VOLTAGE REGULATION THROUGH GATHER AND BROADCAST TECHNIQUES

An Analysis of the Influence of WETO-funded Wind Energy Patents

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